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Configuration parameters design and optimization for plate-fin heat exchangers with serrated fin by multi-objective genetic algorithm

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ABSTRACT

The effect of fin design parameters on the performance of plate-fin heat exchanges was investigated in the paper, in which an improved algorithm combing a Kriging response surface and multi-objective genetic algorithm was used. An ideal gas was adopted as the working fluid and ε-NTU method was utilized to determine the heat transfer and pressure drop. The fin height h, fin space s, fin thickness t and interrupted length l of serrated fin and channel inlet Reynolds number are firstly optimized, while the j factor, f factor and JF factor are optimization goals. The results show that when the inlet channel flow is in the laminar flow ($Re < 1000$), it is beneficial to trade off the j factor and f factor. Furthermore, the total heat flow rate, total annual cost and number of entropy production units of plate-fin heat exchanges are optimized with the specified mass flow rate under given space by multi-objective optimization. Results obtained from the first two objectives and three objectives show that the fin design parameters are very similar except that the latter interrupted length is smaller slightly. A comparison between the results obtained by the previous approaches and the proposed algorithm shows that under the same effectiveness, the annual cost of the proposed algorithm is about 10% lower than the previous ones and it is faster to be converged. Therefore, this study demonstrated that the proposed algorithm is able to optimize the fin design parameter of serrated fin and the obtained results are beneficial to guide the design of plate-fin heat exchanges.

1. Introduction

Heat exchangers are used to transfer thermal energy between two or more media and be known as one of the most essential equipment in almost every industrial plant, including power engineering, aerospace, electronics, automobile, petroleum refineries, cryogenic and chemical industries, etc. Plate-fin heat exchanges (PFHEs) are widely used in gas–gas applications for their high thermal effectiveness, high compactness, low weight, ease of handling multiple streams (up to 20 kinds of media) and low cost. They weigh 95% less than comparable conventional shell-and-tube heat exchangers and provide 1000–2500 square meters of heat transfer per cubic meter of exchanger volume [1]. A typical PFHE main includes nozzle, heater, distributor fin, cover plate, side bar, corrugated fins and cap sheet. However, the most important component of PFHEs is core, which is built by cover plates and layers of fins in a sandwich construction. Depending on the diverse applications, there are many types of fins such as corrugated, louver, perforated, serrated strip and pin fins [2]. While among the many enhanced fin constructions, rectangular serrated fin is widely used. This type of fin is characterized by a high degree of surface compactness, high reliability and substantial heat transfer enhancement due to the boundary layer re-starting at the uninterrupted channels. However, there is, on the other hand, an associated increment in a large pressure drop consequently which leads to higher operational costs. Indeed, it has become necessary to find a trade-off between the heat transfer enhancement and the pressure drop increment.

Unfortunately, the conventional design approaches of PFHEs are difficult to optimize the fin configurations owing to the complexity of PFHEs and the disable design approaches that mainly based on empirical chosen, checking computations with trial-and-error and the results obtained by predecessors. The application of genetic algorithm (GA) in optimization of PFHEs has shown the effectiveness and robust in the few decades. Ozkol et al. [3] employed a GA-based approach for design of PFHEs as an alternative to the previous trial-and-error based approaches and the numerical results indicated that the proposed approach was superior to its previous ones. Xie et al. [4] used the GA to achieve minimum total weight and total annual cost of a cross-flow PFHE with

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Nomenclature

a	heat transfer coefficient, W m^{-2} K^{-1}
A_{chan}	heat transfer area in one channel, m^2
A_{cov}	heat transfer area in cover plate, m^2
A_f	annual cost coefficient
C_A	cost per unit surface area, \$ m^{-2}
C_{Inv}	annual cost of investment, \$ year^{-1}
C_{Ope}	annual cost of operation, \$ year^{-1}
C_{Total}	total annual cost, \$ year^{-1}
D	hydraulic diameter of fin channel, m
f	friction factor
h	height of serrated fin, m
j	colburn factor
k_{el}	price of electrical energy, \$ kW h^{-1}
l	interrupted length of serrated fin, m
L	length of heat exchanger, m
N	fin channel number
Ns	number of entropy production units
NTU	number of transfer units
Nu	Nussle number
Pr	Prandtl number
Q	total rate of heat transfer, W
Re	Reynolds number
s	spacing of serrated fin, m
S_g	entropy production, W kg^{-1} K^{-1}
t	thickness of serrated fin, m
T	temperature, K
u	velocity, m s^{-1}
V	volume flow rate, m^3 s^{-1}

Greek symbols

δ	thickness of cover plate, m
ε	effectiveness
τ	hours of year operation, h
η	compressor efficiency
Φ	rate of heat transfer in one channel, W

Subscripts

B	exchanger (core) length
c	cold side
h	hot side
H	exchanger (core) depth of cold side
in	inlet
L	exchanger (core) width
out	outlet

given constrained condition. Tugrul Ogulata et al. [5] minimized entropy generation number to optimize cross-flow PFHEs. However, only the shape variables were considered as the decision variables while the fin parameters were fixed in the above studies. Mishra [6] exploited a GA to minimize the total annual cost in a cross-flow PFHE where the fin configurations were optimized. Besides many of the new methods had been introduced to heat exchangers design optimization. Peng et al. optimized the total weight and total annual cost of PFHEs by using a GA combined with back propagation neural networks [7] and an improved particle swarm optimization [8]. Hadidi et al. [9] used imperialist competitive algorithm to minimize the cost of shell-and-tube heat exchangers by varying tube length, tube outer diameter, pitch size and baffle spacing. Patel et al. [10] proposed an improved teaching–learning-based optimization algorithm to optimize a Stirling heat engine by considering two and three objective functions simultaneously for the maximization of thermal efficiency, output power and minimization of total pressure drop of the engine. Besides Berrazouane et al. [11] used cuckoo search algorithm to minimize loss of power supply probability, excess energy and levelized energy cost of an optimized fuzzy logic controller. However, no single algorithm is able to outperform the others for all engineering applications, due to continuous improvements in meta-heuristic algorithms. The optimization of PFHEs often faces with more than one objective function and among them are conflicting. Multi-objective genetic algorithm (MOGA) was also successfully applied. Najafi et al. optimized a plate-and-frame heat exchanger [12] and a plate-and-fin heat exchanger [13] by considering maximum the total rate of heat transfer and minimum the total annual cost as two objective functions. Lee et al. [14] used a MOGA to maximize heat transfer rate and minimize pressure drop in PFHEs. Gholap et al. [15] studied the PFHEs by minimizing the energy consumption and material cost as two conflicting objective functions. Liu et al. [16] optimized a recuperator for the maximum heat transfer effectiveness as well as minimum exchanger weight or pressure loss.

The thermodynamic irreversibility is unavoidable in PFHEs due to finite temperature difference heat transfer in the fluid streams and the pressure drops along them. Therefore, the second law based optimization by number of entropy generation unit (Ns) minimization is a very effective method to reduce the amount of lost useful power in PFHEs. Bejan [17] optimized a PFHE through a GA, in which the Ns is optimized with the specified heat duty under given space. Hang et al. [18] considered Ns due to friction, Ns due to heat transfer and total Ns as objective functions by single objective and multi-objective optimization. Wang et al. [19] applied an improved multi-objective cuckoo search algorithm, in which minimum heat transfer and fluid friction number of entropy generation unit were considered to be two objective functions.

The first law (conservation of energy) and second law (entropy generation minimization) of thermodynamics are two main categories for optimization design of PFHEs. However, studies combined with the first and second laws of thermodynamics are lack. In this study, an improved algorithm combing a Kriging response surface and multi-objective genetic algorithm is presented to find optimal four fin design parameters of PFHEs with serrated fin. The total heat flow rate, total annual cost and number of entropy production units of PFHE are considered as objection functions by single objective and multi-objectives optimization with the specified mass flow rate under given space. In addition, in order to guide the design of PFHEs, the j factor, f factor and JF factor are defined as objection functions, while four fin design parameters and channel Reynolds number are considered as optimization parameters. The principal aim of this paper is to investigate the effects of fin design parameters of serrated fin on the performance of PFHEs.

2. Thermal modeling of PFHEs

In this section, the equations for calculating the total heat flow rate, pressure drop, the total annual cost and the modified number of entropy production units of the system are presented.

In Fig. 1, the schematic diagram of a typical serrated fin is shown in detail, in which the fin height h, fin space s, fin thickness t and interrupted length l are considered as the four optimization design parameters. In order to cover the design range of majority of serrated fins in air–air applications, the fin height h is selected from 4.7 mm to 9.5 mm, fin space s is 1.5 mm ~ 3.5 mm, fin thickness t is 0.1 mm ~ 0.5 mm and interrupted length l is 3 mm ~ 9 mm.