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Many-objective optimization of cross-flow plate-fin heat exchanger

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ABSTRACT

This paper presents a rigorous investigation of many-objective (four-objective) optimization of cross flow plate-fin heat exchanger and its comparison with multi-objective (two-objective) optimization. Maximization of effectiveness and minimization of total annual cost, total weight and number of entropy generation units are considered simultaneously as objective functions during many-objective optimization. Multi-objective heat transfer search (MOHTS) algorithm is introduced and applied to obtain a set of Pareto-optimal points of many-objective problem. Application example of plate-fin heat exchanger is presented to demonstrate the effectiveness and accuracy of proposed algorithm. Many objective optimization results form a set of solutions in four dimensional hyper objective space and for visualization it is represented on a two dimension objective space. Thus, results of four-objective optimization are represented by six Pareto fronts in two dimension objective space. These six Pareto fronts are compared with their corresponding two-objective Pareto fronts. Different decision making approaches such as LINMAP, TOPSIS and fuzzy are used to select the final optimal solution from Pareto optimal set of the many-objective optimization. Finally, to reveal the level of conflict between these objectives, distribution of each design variables in their allowable range is also shown in two dimensional objective spaces.

1. Introduction

Heat exchangers are one of the important equipments which servers the purpose of energy conservation through energy recovery. Among several types of heat exchangers, most important one is compact heat exchanger. Plate-fin heat exchanger (PFHE) belongs to the category of compact heat exchanger due to its large heat transfer surface area per unit volume [1,2]. Due to their high thermal effectiveness, plate-fin heat exchangers are widely used in air separation plants, liquefaction plants, aerospace, petrochemical industries and cryogenics applications [3].

Design-optimization of PFHE requires an integrated understanding of thermodynamics, fluid dynamics and cost estimation. Generally, objectives involved in the design optimization of PFHE are thermodynamics (i.e. maximum effectiveness, minimum entropy generation rate, minimum pressure drop etc.) and economics (i.e. minimum cost, minimum weight etc.). The conventional design approach for PFHE is time-consuming, and may not lead to an optimal solution. Hence, application of evolutionary and swarm intelligence based algorithms have gained much attention in design-optimization of PFHE.

Earlier, several investigators used various optimization techniques with different methodologies and objective functions to optimize PFHE. However, their investigation was focused on single objective optimization or multi-objective (i.e. two or three objective) optimization. Wen et al. [4] carried out a thermodynamic optimization of PFHE. The authors considered two conflicting objectives namely, Colburn factor and friction factor for optimization and used Genetic algorithm (GA) as an optimization tool. Du et al. [5] focused on a double flow plate-fin heat exchanger for improving its thermal and hydraulic behaviour using GA. Turgut [6] investigated Hybrid Chaotic Quantum behaved Particle Swarm Optimization (HCQPSO) algorithm for minimizing the heat transfer area and total pressure drop of PFHE. Sanaye and Hajabdollahi [7] performed a simultaneous optimization of total cost and effectiveness using a design which featured NSGA-II and PFHE. Rao and patel [8] performed a multi-objective optimization of PFHE with effectiveness and total cost of heat exchanger as objective functions. The authors used modified version of teaching learning based optimization (TLBO) algorithm as an optimization tool.

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Nomenclature

A	heat transfer area (m^2)
a	annual co-efficient factor
A_{ff}	free flow area (m^2)
C_A	cost per unit area (\$/m^2)
C_p	specific heat (J/kg K)
C_{inv}	initial cost (\$)
C_{ope}	operating cost (\$)
C^*	heat capacity ratio
d_h	hydraulic diameter (m)
f	Fanning friction factor
G	mass flux velocity (kg/m^2 s)
h	convective heat transfer co-efficient (W/m^2 K)
H	height of fin (m)
i_r	rate of interest (%)
j	Colburn factor
k_{el}	electricity price (\$/MWh)
l_f	fin offset length (m)
L	heat exchanger length (m)
LINMAP	Linear Programming Technique for Multidimensional Analysis of Preference
m	mass flow rate (kg/s)
n	fin frequency (no. of fins/m)
N_h	number of hot side layer
N_c	number of cold side layer
N_S	number of entropy generation unit
NTU	number of transfer units
P	Pressure (kPa)
Pr	Prandtl number
ΔP	pressure drop (kPa)
Re	Reynolds number
fs	fin spacing (m)
t	fin thickness (m)
t_d	depreciation time
T	temperature (K)
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TAC	total annual cost
U	overall heat transfer co-efficient (W/m^2 K)
V	volume flow rate (m^3/s)
W_t	total weight (kg)

Greek letters

ε	effectiveness
μ	viscosity (N.s/m^2)
ρ	density (kg/m^3)
η	compressor efficiency
τ	hour of operation
δ	Dimensionless parameter, $t\big/l_f$
α	Dimensionless parameter, $\left(1\!/\!n - t\right)\big/(H-t)$
γ	Dimensionless parameter, $t\big/\left(1\!/\!n - t\right)$

Subscripts

h	hot
c	cold
max	maximum
min	minimum
tot	total

Wang and Li [9] introduced and applied an improved multi-objective cuckoo search (IMOCS) algorithm for optimization of PFHE. The authors considered conflicting thermo-economic objectives for optimization. Hajabdollahi [10] investigated the effect of non-similar fins in thermo-economic optimization of plate fin heat exchanger. They considered total annual cost and effectiveness of heat exchanger as objective functions and utilized NSGA-II for optimization. Hadidi [11] employed biogeography-based optimization (BBO) algorithm for optimization of heat transfer area and total pressure drop of the PFHE. Patel and Savsani [12] obtained a Pareto front between conflicting thermodynamic and economic objectives of PFHE by implementing multi-objective improved TLBO (MO-ITLBO) algorithm.

Wang et al. [13] presented few layer pattern criterion models to determine optimal stacking pattern of multi-stream plate-fin heat exchanger (MPFHE). Authors have developed these models by employing genetic algorithm and observed that the performance of MPFHE in relation to heat transfer and fluid flow was effectively improved by the optimization design of layer pattern. Zaho and Li [14] developed an effective layer pattern optimization model for multi-stream plate-fin heat exchanger using genetic algorithm. Zhou et al. [15] presented an optimization model for PFHE based on entropy generation minimization method. They considered specific entropy generation rate as an objective function and total heat transfer area of PFHE as a constraint. Yousefi et al. [16] presented a learning automata based particle swarm optimization employed to multi-stage thermo-economical optimization of compact heat exchangers. Several other investigators performed single objective [17–26] or multi-objective (two or three objective) [27–34] optimization of PFHE for thermodynamic [17–20,24–26,28,29], economic [21–23] or thermo-economic [27,30–34] objectives with different optimization strategies.

Thus, it can be observed from literature that researchers have carried out economical optimization, thermodynamic optimization or thermo-economic optimization of PFHE for single or multi-objective (two or three objective) consideration. However, many-objective optimization of PFHE is not yet observed in literature. Considering this fact, efforts have been put in the present work to perform a many-objective (i.e. four-objective) optimization of PFHE. Many-objective consideration results in more realistic design of PFHE and end user can select any optimal design from it depending on their requirements.

Further, as an optimization tool, heat transfer search (HTS) algorithm [35] is implemented in the present work. Heat transfer search is a recently developed meta-heuristic algorithm based on natural law of thermodynamics and heat transfer [35]. In this work, a multi-objective variant of heat transfer search (MOHTS) algorithm is presented to address many-objective optimization problem of PFHE. The proposed algorithm uses a grid-based approach in order to keep diversity in the external archive. Pareto dominance is incorporated into the MOHTS algorithm in order to allow this heuristic to handle problems with several objective functions. Qualities of the solution are computed based on the Pareto dominance notion in the proposed algorithm.

Main contributions of the present work are (i) Many-objective optimization of PFHE to maximize effectiveness and minimize total annual cost, total weight and number of entropy generation units simultaneously. (ii) To introduce multi-objective variant of the heat transfer search (MOHTS) algorithm and employed it to solve many-objective optimization problem of PFHE (iii) To