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Thermal-hydraulic optimization of plate heat exchanger: A multi-objective approach

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ABSTRACT

In the present work, thermal-hydraulic optimization of plate heat exchanger is investigated. Maximization of overall heat transfer coefficient and minimization of total pressure drop considered simultaneously as objective functions during multi-objective optimization. Multi-objective heat transfer search algorithm is applied to obtain a set of Pareto-optimal points for conflicting objectives. An application example of plate heat exchanger is presented to identify conflicting thermal-hydraulic behaviour. Eight geometric design variables which include port diameter, a horizontal distance of ports, a vertical distance of ports, length of compact plates, plate thickness, chevron angle, enlargement factor and number of plates are investigated for optimization. Decision-making method is adopted to select the final optimal solution from Pareto points. Distribution of each design variables corresponding to Pareto optimal points is presented to identify its effect on conflict behaviour of the thermal-hydraulic function. The sensitivity of design variables to the optimized value of the thermal-hydraulic function is also presented and discussed. Finally, the validation of the present work is carried out by experimentation on plate heat exchanger. The comparative results revels that 8.87% deviation in overall heat transfer coefficient and 9.96% deviation in total pressure drop are observed between optimization and experimental results.

1. Introduction

A heat exchanger is an important industrial device used to transfer heat between hot and cold stream for energy conservation. Types of heat exchanger used for energy conservation in industries depend on the kind of fluid involves in heat exchange process. Shell and tube heat exchanger (STHE) is used for the liquid to liquid or gas to liquid heat transfer while compact heat exchanger (CHE) is used for gas to gas, gas to liquid or liquid to liquid heat transfer [1]. One of the important CHE is plate heat exchanger (PHE). PHEs are widely used in Petroleum, chemical processing, food & beverages, cryogenics, and pharmaceutical industries. The distingue features of PHEs are its high surface area density and thermal effectiveness, resulting in reduced size, weight, and space compared to other types of heat exchanger [2]. On the other end, high hydraulic losses (i.e. pressure drop) involved in PHEs. Thus, the trade-off between thermal and hydraulic behaviour is always required to reach at optimum design of PHEs. Further, large number of design parameters is involved in the design of PHEs that should satisfy the geometric/operating constraints and heat duty requirements. As a result, metaheuristic algorithms are more suitable to obtain the optimized design of PHEs as compared to conventional optimization methods. Generally, objectives involved in the design optimization of PHE are thermodynamics (i.e. maximum effectiveness, minimum entropy generation rate, minimum pressure drop, etc.) and economics (i.e. minimum cost, minimum weight, etc.).

Earlier, researchers had carried out different types of numerical works to optimize PHEs design with different methodologies. Hajabdollahi et al. [3] obtained optimized geometric parameters of gasket plate heat exchanger for maximum effectiveness and minimum total cost by adapting NSGA-II. Hajabdollahi et al. [4] presented the comparative study of gasket plate and shell and tube heat exchangers from the economic point of view by using a genetic algorithm (GA). Najafi and Najafi [5] performed a multi-objective optimization of PHE with pressure drop and heat transfer coefficient of a heat exchanger as objective functions. The authors used NSGA-II as an optimization tool. Lee and Lee [6] carried out a thermodynamic optimization of PHE. The authors considered two conflicting objectives namely, Colburn factor and friction factor for optimization and used GA as an optimization tool. Further, authors also developed the correlation for Colburn factor and friction factor. Arsenyeva et al. [7] proposed mathematical model

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Nomenclature

A_e	effective heat transfer area (mm^2)
A_1	heat transfer area of plate (mm^2)
A_{1p}	projected area (mm^2)
b	mean channel flow gap (mm)
C	heat capacity (W/K)
C^*	heat capacity ratio (−)
D_h	hydraulic diameter (mm)
D_p	port diameter (mm)
f	friction factor (−)
G	mass flux in each channel ($kg/m^2.s$)
G_p	mass flux in port ($kg/m^2.s$)
h	heat transfer coefficient ($W/m^2.K$)
k	thermal conductivity (W/m.K)
L_h	horizontal distance between ports (mm)
L_p	length of compact plate (mm)
L_v	vertical distance between ports (mm)
L_w	plate width (mm)
m	mass flow rate (kg/s)
N	number of plates (−)
N_{cp}	number of channels per pass (−)
N_e	effective number of plates (−)
N_p	number of pass (−)
NTU	number of transfer units (−)
n, n_1	coefficient for heat transfer coefficient (−)
p	plate pitch (mm)
Pr	Prandtl number (−)
ΔP	pressure drop (kPa)
Re	Reynolds number (−)
R_f	fouling factor (m^2 K/W)
t	plate thickness (mm)
U	overall heat transfer co-efficient (kW/m^2 K)

Greek letters

ρ	density (kg/m^3)
ε	effectiveness (−)
μ	viscosity ($N.s/m^2$)
ϕ	enlargement factor (−)

Subscripts

h	hot
c	cold
max	maximum
min	minimum

based area optimization of a multi-pass plate-and-frame heat exchanger. Gut and Pinto [8,9] presented a mathematical model of gasket plate heat exchanger [8] and perform shape optimization [9] of that model. Further, authors presented a screening method for selection of optimal configurations of plate heat exchangers. Wang and Sunden [10] used derivative-based optimization method for the economic optimization of plate heat exchanger. Durmus et al. [11] carried out an experimental investigation of plate heat exchanger having different surface geometry. They proposed heat transfer, friction factor and exergy loss correlations for plate heat exchanger based on experimental results. Zhu and Zhang [12] perform heat transfer area optimization of plate heat exchanger used for the geothermal heating application.

Apart from plate heat exchanger, efforts are put by researchers to optimize other types of heat exchangers with different objectives and methodology. For example, Patel and Rao performed optimization of shell and tube heat exchanger [13–15], plate-fin heat exchanger [15,16], and regenerative heat exchanger [17] with different optimization algorithms. Patel and Savsani [18] presented multi-objective optimization of a plate-fin heat exchanger. Nobile et al. performed multi-objective optimization of convective periodic and wavy channels [19–21], numerical analysis of fluid flow and heat transfer in periodic wavy channels [22], and shape optimization of a tube bundle in cross-flow [23]. Hajabdollahi et al. performed optimization of shell and tube [24–27] and plate-fin [28,29] heat exchangers for single objective and multi-objective consideration. Raja et al. presented optimization of shell and tube heat exchanger [30], plate-fin heat exchanger [31], and rotary regenerator [32]. Yousefi et al. carried out the optimization of plate-fin heat exchanger [33–35] and compact heat exchanger [36,37] with evolutionary algorithms.

Main contributions of the present work are (i) To develop multi-objective thermal-hydraulic optimization problem of plate heat exchanger to maximize overall heat transfer coefficient and minimize total pressure drop. (ii) To employed multi-objective variant of the heat transfer search (MOHTS) algorithm to solve the thermal-hydraulic optimization problem of PHE. (iii) Select a final optimal solution from the Pareto optimal set with the help of LINMAP (Linear Programming Technique for Multidimensional Analysis of Preference) decision-making approach. (iv) Identify the underlying relationship of decision variables during thermal-hydraulic optimization and (v) Investigate sensitivity of design variable on the optimized value of thermal-hydraulic objective functions (vi) Validate the optimization results by experimental investigation.

Remaining sections of this paper are organized as follows. Section 2 presents the thermal-hydraulic modelling and the objective functions formulation of PHE. Section 3 describes the heat transfer search algorithm. Section 4 explains multi-objective heat transfer search algorithm. Section 5 presents the application example of PHE, results-discussion and experimental validation. Finally, the conclusion of the present work is discussed in section 6.

2. Modelling formulation

This section describes thermal-hydraulic modelling of PHE, objective function formulation, design variables, and constraints involved in PHE design optimization.

2.1. Thermal and hydraulic formulation

Detailed geometry of counter flow PHE with chevron plates is shown in Fig. 1. In this work, ε-NTU approach is utilized to predict the performance of PHE [1]. The PHE is assumed to running under a steady state, with negligible heat loss and uniform velocities. Further, heat transfer coefficients are assumed to be uniform and constant. Table 1 presents thermal and hydraulic model formulation of PHE.

2.2. Objective functions

In this work, a multi-objective optimization is carried out between conflicting objectives. Maximization of overall heat transfer coefficient and minimization of the total pressure drop of PHE are considered as objectives. For counter flow PHE, overall heat transfer coefficient is calculated using following equation,

$$U = \frac{1}{\left(1/h_h\right) + R_{f,h} + \left(1/h_c\right) + R_{f,c} + \left(t/k\right)_w} \tag{17}$$

where, t and k are wall thickness and wall thermal conductivity respectively.

Similarly, the total pressure drop of PHE is summation of the