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Optimization of plate-fin heat exchangers by minimizing specific entropy generation rate

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ABSTRACT

In the present study, an optimization model is developed for plate-fin heat exchangers (PFHEs) based on the entropy generation minimization method. In the modeling, the entropy generation rate per unit partition plate area, i.e., specific entropy generation rate is proposed as an optimization objective function and the total heat transfer area of a PFHE is considered as a constraint. The model takes into account the irreversibility due to both irreversible heat transfer and pressure drop. The analysis of optimal allocation of total heat transfer area between the hot- and cold-side for a PFHE is conducted with a case study. The results show that optimal geometric parameters of a PFHE such as the fin spacing and fin height on both the hot- and cold-sides can be achieved when the finite total heat transfer area is optimally allocated with minimizing the specific entropy generation rate. In addition, the effects of total heat transfer area, heat transfer rate, as well as the ratio of mass flow rate between the cold- and hot-side fluid on the specific entropy generation rate and optimal allocation ratio of total heat transfer area are also analyzed.

1. Introduction

Plate-fin heat exchangers (PFHEs) have been used in the aircraft industry, air separation and chemical plants over past decades. They are very compact heat exchangers built to a high specification for various industrial applications. In a design process, the optimal design of PFHEs is an important aspect and highly desirable for most practical applications. This can give rise to certain benefits for the thermal and economical performances of PFHEs. Therefore, solving the optimal design problem for PFHEs by means of optimization techniques has been studied extensively.

Among the optimization methods available for heat exchanger optimal design, the pioneer entropy generation minimization (EGM) approach introduced by Bejan [1] has been widely used as a performance evaluation criterion in geometric optimization of various types of heat exchangers [2–9]. Shi and Dong [2] presented an entropy generation investigation on a rotating helical tube heat exchanger concerning optimization of both total entropy generation and its components, i.e., the entropy generation from friction pressure drop and heat transfer across a finite temperature difference. Li and Lai [3] investigated thermodynamic performance of borehole ground heat exchangers with a single U-tube by the EGM method and demonstrated thermodynamic optimal parameters of ground heat exchangers. Pussoli et al. [4] investigated optimal heat exchanger configurations of peripheral finned-tube evaporators and determined the optimal characteristics of heat exchangers. Ye and Lee [5] performed a study to investigate the refrigerant circuitry design of fin-and-tube condenser based on EGM, in which the refrigerant side performance was analyzed using entropy generation number to determine the optimal number of passes on the refrigerant side. Leong et al. [6] conducted the heat transfer and entropy generation comparison of three different types of heat exchangers and evaluated the suitability of nanofluid as a coolant in a heat exchanger. Kotcioglu et al. [7] made a second law analysis of a cross-flow heat exchanger with a new winglet-type convergent–divergent longitudinal vortex generator on the basis of the entropy generation minimization. Guo et al. [8] developed an optimization design approach on a shell-and-tube heat exchanger using the dimensionless entropy generation rate obtained by scaling the entropy generation on the ratio of the heat transfer rate to the inlet temperature of cold fluid as the objective function. Mohamed [9] analyzed the entropy generation resulting from heat transfer and fluid flow thermodynamic irreversibilities in a counter flow double pipe heat exchanger.

The studies of optimizing PFHEs based on entropy generation minimization have also been widely performed in recent years [10–16]. Babaelahi et al. [10] described multi-objective optimization of a cross-flow PFHE using an entropy generation

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Nomenclature

A	heat transfer area (m^2)
a	cross-section area of the channel (m^2)
c_p	specific heat (J/kg K)
D_h	hydraulic diameter (m)
H	fin height (m)
h	heat transfer coefficient (W/m^2 K)
U	overall heat transfer coefficient (W/m^2 K)
L	heat exchanger length (m)
$\dot{m}$	mass flow rate (kg/s)
m	$m = \sqrt{2h/(\lambda_i \delta)}$ (1/m)
n	number of fin channels
P'	inlet pressure of working fluid (MPa)
P''	outlet pressure of working fluid (MPa)
Pr	Prandtl number
Δp	pressure drop (Pa)
$\dot{Q}$	heat transfer rate (W)
R	gas constant
Re	Reynolds number
$\dot{S}_g$	total entropy generation rate (W/K)
$\dot{S}_{gt}$	entropy generation rate due to heat transfer (W/K)
$\dot{S}_{gp}$	entropy generation rate due to pressure drop (W/K)
$\dot{S}_{gu}$	specific entropy generation rate (W/m^2 K)
s_f	fin spacing (m)
T'	inlet temperature of working fluid (K)
T''	outlet temperature of working fluid (K)
ΔT_m	logarithmic mean temperature difference (K)
u_m	average velocity of fluid (m/s)
x	ratio of hot-side heat transfer area to total heat transfer area

Greek symbols

λ	thermal conductivity of working fluid (W/m K)
λ_i	thermal conductivity of the intermediate partition plate (W/m K)
δ	fin thickness (m)
δ_i	thickness of the intermediate plate (m)
η_f	fin efficiency
η_0	overall fin surface efficiency
ζ	mass flow rate ratio of cold-side fluid to hot-side fluid
μ	dynamic viscosity (Pa)
ρ	fluid density (kg/m^3)

Subscripts

c	cold side
h	hot side
i	intermediate
f	fin
o	total

minimization technique, and achieved the best trade-off between entropy generation related to heat transfer and entropy generation related to fluid friction. Zarea et al. [11] conducted an optimization analysis on a cross flow PFHE with offset strip fin based on the second law of thermodynamics and minimizations of entropy generation units by applying the Bees Algorithm under constraints of specific heat duty, space restriction and permitted pressure drop. Ahmadi et al. [12] proposed a theoretical model of optimally designing a cross-flow PFHE by minimizing the entropy generation units and total annual cost simultaneously. Youseli et al. [13] optimized a cross-flow PFHE through minimizing number of total entropy generation units under a specific heat duty and pressure drop constraints by employing Imperialist Competitive Algorithm. Rao and Patel [14] studied the optimization of a cross flow PFHE with total number of entropy generation units, total volume and total annual cost as objective functions by exploring the use of particle swarm optimization algorithm. Zhang [15] developed a general three-dimensional distributed parameter model for the optimal design of a PFHE with considering the entropy generation minimization by employing the genetic algorithm. Manish et al. minimized the number of entropy generation units by employing the genetic algorithm to optimize a cross flow PFHE with offset-strip fins for a specified heat duty under given space restrictions [16]. Overall, the optimal level of design parameters for PFHEs was obtained through the EGM method with different models or solution approaches under given constrained conditions. Thus, the EGM methodology can be a good alternative for optimization problems containing PFHEs.

The application of the EGM technique to the optimum design of PFHEs relies on the measure criteria of entropy generation and specified constraints. To the best knowledge of the authors, however, most of the research concentrates on the overall entropy generation rate or the number of entropy generation units. In fact, PFHEs as compact heat exchangers are characterized by a large heat transfer surface area per unit volume. Heat transfer areas and configurations in PFHEs are crucial matters for the optimal design. Therefore, it becomes necessary to establish a relationship between entropy generation and heat transfer areas. In the present paper, the entropy generation rate per unit area of the intermediate partition plate (called as the specific entropy generation rate here) is considered as an objective function to perform the optimization of a PFHE. The optimization aims at finding the minimum specific entropy generation rate by accounting for the finite size constraint of total heat transfer area. For this purpose, this paper presents an optimization model based on LMTD (logarithmic mean temperature difference) method for optimal design of PFHEs by minimizing specific entropy generation rate. Moreover, this paper discusses and analyzes implications and applications of the optimization model with a case study. In this work, it is desired to estimate the feasibility of this introduced optimization model for the optimum design of plate-fin heat exchangers.

2. Mathematical modeling

The heat exchanger under study is a plate-fin type heat exchanger with plain fins. Fig. 1 gives a schematic diagram of a plate-fin heat exchanger, in which main geometrical and operating parameters are also provided. As shown in Fig. 1, for the computational section, the heat exchanger has two channels. The plate-fin heat exchanger runs in a counter-flow mode: the hot fluid flows in one channel, whereas the cold fluid flows in the other channel in an opposite direction.

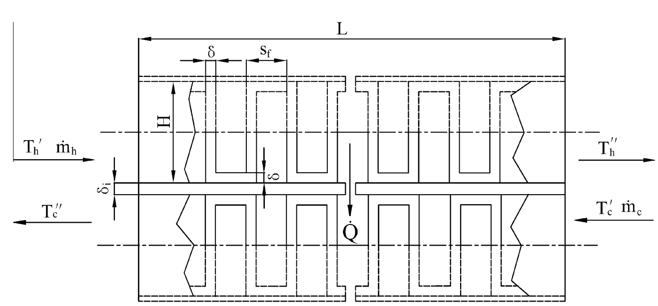

Fig. 1. Schematic diagram of a plate-fin heat exchanger.