International Journal of Heat and Mass Transfer 82 (2015) 510–520

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental investigation on the thermal performance of multi-stream plate-fin heat exchanger based on genetic algorithm layer pattern design

Zhe Wang [a], Yanzhong Li [a,b,*], Min Zhao [a]

[a] School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 27 April 2014
Received in revised form 14 October 2014
Accepted 7 November 2014
Available online 26 November 2014

Keywords:
Multi-stream plate-fin heat exchanger
Layer pattern
Optimization design
Genetic algorithm
Thermal performance
Experimental verification

ABSTRACT

Efficient approaches are imperative for the design of the layer pattern of multi-stream plate-fin heat exchangers (MPFHE) to obtain enhanced thermal performance. This paper presents few layer pattern criterion models to determine optimal stacking pattern. These models were developed by employing a genetic algorithm with binary chromosome ring representing alternatively placed hot and cold layer fluid streams. The method of dual fitness alternating optimization functions was used for conducting local heat energy balance and single layer thermal load difference. The zigzag pattern weighted deviation of the cumulative heat load σ was evaluated for the layer pattern. An experimental study was conducted on layer pattern to test the optimality of the stacking pattern. The experimental data and HTFS MUSE simulation results were found to be in agreement. The optimized results showed that the smallest value of σ was in the range of 0.05–0.20, and that the average thermal efficiency of exchanger was higher than 98%. From these results it was concluded that the performance of MPFHE in relation to heat transfer and fluid flow was effectively improved by the optimization design of the genetic algorithm (GA) layer pattern.

1. Introduction

Multi-stream plate-fin heat exchangers (MPFHE) are widely used in the petrochemical, gas treatment, liquefied natural gas and air separation industries. They are economical in investment and operational costs due to the compact design; small temperature differences between the heat transfer fluids, low pressure drops and high heat transfer rates with a wide choice of aluminum fins. Several streams can be processed simultaneously in a single compact heat exchanger unit. The MPFHE are apparently different from the two fluid heat exchangers and are affected by a variety of fluid flows and a plurality of temperature field superposition effects of the heat exchanger. These factors could cause direct or indirect crossover of temperature and internal heat loss [1,2]. When the distribution arrangement of the cold and hot fluid layers is incorrect, the thermal efficiency of MPFHE is greatly reduced. Simultaneously, the heat exchanger experiences thermal stresses which adversely impact its strength and service life. Due to the large number of layers that participate in heat transfer the number of cold and hot fluids can be as many as a dozen. So the possible arrangement of layer pattern can amount to several thousands. It is difficult to use either a simple enumeration or traditional gradient optimization method for optimizing the heat transfer layer pattern. Because of the coupling of heat transfer between the layers, it is also difficult to analyze and formulate a theory to guide the arrangement of passages [3]. It still remains as a trial-and-error process. The HTFS MUSE can perform a wide range of simulations on the plate-fin heat exchangers to evaluate the performance by an existing layer pattern, i.e. in calculating the stream outlet conditions for each stream; the program does independent calculations for each layer in the exchanger and then determines the metal temperature profile along every parting sheet between the layers [4]. This software can effectively evaluate the quality of a layer pattern specified by the users, but it is unsuitable for the design and optimization of layer pattern. Therefore, the layer pattern problem still remains as an active area of research on MPFHE.

Fan [2] proposed in 1966 an isolation layer pattern based on semi-empirical principle to prevent the cross over in temperature and internal heat loss. In 2013 Zhao [5] used the dual fitness functions that act on genetic algorithm (GA) alternatively to obtain a highly efficient automatic layer pattern arrangement. For almost half a century extensive research has been conducted, the most representative of which are the following. In 1976 Suessmann [6] proposed the heat load of cumulative zigzag curve to evaluate

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* Corresponding author at: School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China. Tel.: +86 29 82668725; fax: +86 29 82668789.

E-mail address: yzli-epe@mail.xjtu.edu.cn (Y. Li).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.11.036

Nomenclature

Cp_i	specific heat of stream i, kJ kg^{-1} K^{-1}
c_j	cold stream i of MPFHE, $j = 1, 2, \ldots, n_c$
E_i	excess heat load of each hot/cold layer bunch in layer pattern ring
h_i	hot stream i of MPFHE, $i = 1, 2, \ldots, n_h$
L_n	the line length of zigzag curve
$\dot{m}_i$	mass flow rate of stream i, kg/h or kg/s
n	number of layers in the chromosome
n_c	number of different cold streams in MPFHE
n_h	number of different hot streams in MPFHE
N	total number of layers of MPFHE
N_i	number of layers of stream i
P_{out}	outlet pressure of stream i, MPa
P_i	inlet pressure of stream i, MPa
q_i	heat load per layer of stream i, kW
$\dot{Q}_{i,j}$	heat transfer rate between fluid streams i and j, kW
S_n	cumulative heat load for each layer, kW
S_n^{mid}	midpoint of S_n
$\bar{S}_n^{mid}$	arithmetic-mean of S_n^{mid}
t_i	outlet temperature of stream i, K
T_{in}	inlet temperature of stream i, K
T_{out}	outlet temperature of stream i, K
w_i	weighting, respectively
$(UA)_{i,j}$	heat conductance between fluid streams i and j, W K^{-1}
$LMTD_{ideal}$	ideal logarithmic mean temperature difference
NTU_{ideal}	ideal number of heat transfer units
σ	the zigzag pattern weighted deviation of the cumulative heat load
η	layer arrangement thermal efficiency of the heat exchanger
f^*	heat exchanger layer friction resistance factor

the quality of layer pattern and suggested minimization of the excess heat load of layer pattern. This criterion is based on local heat load balancing. In the 90s Prasad [7–11] published several papers to elucidate the influence of layer pattern on the performance of MPFHE, surface temperature field, fin efficiency and flow distribution from different aspects. And a quantitative evaluation of the merits of the performance of the heat exchanger was conducted using the finite difference calculation and constant wall temperature method. They presented a comprehensive MPFHEs design study, but the layer pattern optimization was not included in these researches. In the year 2000, Renesume [12] expanded the theory of hybrid layer pattern and showed that the proportion of hot and cold fluid layer number between 0.5 and 2 had a significant effect on the exchanger performance. Peng [13] suggested uniform evaluation of fluid outlet temperature. Guomin [14] employed multi-field synergy principle to optimize the fluid layout layer pattern of MPFHE. Lu [15] proposed temperature difference uniformity factor to evaluate the layer pattern effect on the performance of MPFHE. Guo and Cui [16] proposed a structured layer pattern principle of continuity, and observed that small variations in the layer pattern have insignificant effect on the heat exchanger performance. However, this arrangement gave a regional continuity. In the year 2012, Zhao et al. [17] proposed the criterion of equal temperature difference and equal number of heat transfer unit layer pattern for three stream plate fin heat exchanger.

For the optimization of heat exchanger structure design, intelligent algorithms are widely used in the recent years [18,19]. For example, Xie et al. [20] used the minimum volume and economic costs fitness function to optimize the structural size of plate-fin heat exchangers. Mishra et al. [21] applied the second law of entropy production unit fitness function. Recently, due to its negligible dependence on the problems being studied and the powerful searching ability and robustness in solving complex problems, the GA is widely used in the optimization design problems of heat exchangers. For example, Hilbert et al. [22] used GA to optimize the blade shape of a heat exchanger, considering the coupled solution of the flow/heat transfer processes. Amini and Bazargan [23] employed GA with 11 variables to optimize the design parameters of a shell-and-tube heat exchanger. However, researchers seldom apply meta-heuristic algorithms to optimize the layer pattern of MPFHE. Ghosh [24] applied GA to solve the MPFHE layer pattern problem, and established that this model is suitable for optimizing the arrangement for 3–8 different fluid layers. But with increasing number of layers, the optimization of layer pattern becomes highly complicated.

Most of the experimental study on MPFHE focused on the flow distribution and header structure [25,26]. Experimental investigations based on the layer pattern designs are scant. For the industrial applications, the MPFHE can be arranged in the form of given layers, and a computer model can be employed to predict the heat transfer and flow performance [27]. But for the MPFHE design, a method to create an optimal layer pattern and then to obtain a solution for its performance at given conditions is not available.

This paper attempts to address the practical problem stated above by employing genetic algorithm optimization and experimental verification. It is expected that this approach would provide a solution for obtaining an improved layer pattern. The paper is organized in several sections: The Section 2 deals with the design criterion for mathematical formulation and the dual fitness function genetic algorithm optimization model; The Section 2.4 explains the validity of the proposed GA-based optimization process, and two case studies for its verification. The experimental studies on the layer pattern design are explained in Section 3. The experimental verification of the layer pattern optimization is expressed and the results are discussed in the Section 4. The conclusions are given in the Section 5.

2. Layer pattern design

2.1. Design criterion

2.1.1. The local heat load balance criterion

For the local heat load balancing mode, the heat exchanger was divided into a number of transverse heat load balancing units. These units should be as small as possible and also follow the layer pattern criterion. Then the accumulated layer heat load is positioned onto the zigzag diagram, through the study of deviation of zigzag curve from the zero line level and evaluation by the layer pattern quality. The local heat load balance criterion model can be expressed as:

$$q_{h_i} = \frac{\dot{m}_{h_i} Cp_{h_i} (t_{h_i} - T_{h_i})}{N_{h_i}}, \quad i = 1, 2, \ldots, n_h \tag{1}$$

$$q_{c_j} = \frac{\dot{m}_{c_j} Cp_{c_j} (t_{c_j} - T_{c_j})}{N_{c_j}}, \quad j = 1, 2, \ldots, n_c \tag{2}$$

In the above equations, q_{h_i} is heat energy transferred from the hot stream h_i, the sign for which is "–". While q_{c_j} is heat energy gained