International Journal of Heat and Mass Transfer 119 (2018) 282–294

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Optimization investigation on configuration parameters of serrated fin in plate-fin heat exchanger based on fluid structure interaction analysis

Jian Wen [a], Ke Li [a], Xing Zhang [a], Chunlong Wang [a], Simin Wang [b],*, Jiyuan Tu [c]

[a] *Department of Refrigeration and Cryogenics Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China*
[b] *Department of Process Equipment and Control Engineering, School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an 710049, China*
[c] *Institute of Nuclear and New Energy Technology, Key laboratory of Advanced Reactor Engineering and safety, Ministry of Education, Tsinghua University, Beijing 100084, China*

ARTICLE INFO

Article history:
Received 17 April 2017
Received in revised form 13 October 2017
Accepted 13 November 2017

Keywords:
Plate-fin heat exchanger
Serrated fin
Stress analysis
Response surface
Analysis of variance
Multi-Objective Genetic Algorithm

ABSTRACT

The comprehensive performance of serrated fin in plate-fin heat exchangers (PFHEs) is numerically studied based on fluid structure interaction (FSI) analysis in this paper. Based on Full 2nd-Order Polynomial response surface (RS) and analysis of variance (ANOVA), the effects and second order interaction effects of the fin height, fin space, fin thickness and fin interrupted length on heat transfer, flow resistance and stress are quantitatively and thoroughly assessed. The results show that the heat transfer is the most sensitive to fin interrupted length, and the flow resistance and the maximum stress are the most sensitive to fin thickness. The interaction effect of the fin space and fin interrupted length is the strongest when the j factor is set as objective function, while the interaction effect of the fin space and fin thickness is the strongest when the f factor or maximum stress is set as objective function. Based on Full 2nd-Order Polynomial RS, Multi-Objective Genetic Algorithm (MOGA) is applied to optimize the fin structure comprehensively, with enhancing heat transfer, decreasing pressure drop and stress set as objectives. To demonstrate the effectiveness of optimized structures, a comprasion between the original design and optimized structures is performed. The results show that the JF factor of optimized structures 2 and 3 increases by 23.0% and 19.7% respectively, and the maximum stress decreases by 5.8% and 15.2% respectively. The MOGA offers theorectical guidance for optimization design of PFHE.

1. Introduction

Serrated fin is widely used in PFHE for its compactness of the surfaces [1], being characterized by large heat transfer area in per unit volume and substantial heat transfer enhancement due to the boundary layer restarting at the interrupted channels formed by fins. However, there is an associated increase in a large pressure drop for the interrupted arrays. In recent years, a lot of research achievements about surface characteristics of PFHE, analysis of heat transfer and flow pattern and design of structure have been obtained.

Much research work focused on heat transfer and flow pattern of PFHE. Kays and London [2] systematically listed performance parameters of 21 kinds of aviation aluminum serrated plate-fin structure with condensing steam heating the normal temperature air in wind tunnel experiments. Bhowmik and Lee [3] analyzed fluid flow and heat transfer characteristics of offset strip fins in the laminar, transition and turbulent regions by fitting the general correlations for the f and j factors. Ranganayakulu and Luo [4] employed a single-blow transient test technique to measure the Colburn j factor versus Reynolds number characteristics of high efficiency compact heat exchanger surfaces having offset and wavy fins by using the NTU values estimated for 5 types of fins based on experimental date. Zhang and Mehendale [5] constructed the experimental facility and the related data acquisition system to study liquid-gas flow distribution in a PFHE. Li et al. [6] discussed the heat transfer enhancement mechanism for TD (Transverse Direction) type serrated fins by field synergy principle (FSP) theory on the foundation of numerically and experimentally studying the heat transfer and pressure drop characteristics of TD type aluminum serrated fins in compact heat exchanger. Wen and Yang [7,8] optimized the configuration of serrated fin in PFHE with genetic algorithm combined with Kriging response surface method (RSM), finally obtaining a set of optimal solutions with the objectives of maximum of j factor and minimum of f factor. Furthermore, the total heat flow rate, total annual cost and number of entropy production units of PFHE were optimized with the specified mass flow rate under given space by MOGA. Segundo and Amososo [9] presented an optimization of PFHEs considering as objective

---

* Corresponding author.
E-mail address: smwang@mail.xjtu.edu.cn (S. Wang).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.058
0017-9310/© 2017 Elsevier Ltd. All rights reserved.

Nomenclature

Latin symbols

A_w	total heat transfer area of fin channel, m^2
A_c	area of fin channel, m^2
A_{in}	inlet area of extension
c_p	specific heat, W kg^{-1} K^{-1}
D_h	equivalent diameter of the plate-fin structure, m
df	degrees of freedom
f	friction factor
h	height of serrated fin, m
h_c	heat transfer coefficient, W m^2 K^{-1}
j	Colburn factor
JF	JF factor
l	interrupted length of serrated fin, m
L	length of heat exchanger, m
L_e	length of extension, m
M	mass flow rate, kg s^{-1}
MS	mean square
Nu	Nusselt number
Pr	Prandtl number
ΔP	differential pressure, Pa
Q	total rate of heat transfer, W
Re	Reynolds number
s	spacing of serrated fin, m
SS	sum of squares
t	thickness of serrated fin, m
Δt_m	logarithmic mean temperature difference, K
T	temperature, K
T_{out}	outlet temperature, K
T_{in}	inlet temperature, K
u	velocity, m s^{-1}
u_c	velocity in fin channel, m s^{-1}
u_{in}	inlet velocity, m s^{-1}
Δt_m	logarithmic mean temperature difference, K

Greek symbols

λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity of fluid, Pa s
ρ	density, kg·m^{-3}
σ	stress, MPa
τ	shear force, MPa

Subscripts

c	channel
e	extension
in	inlet
out	outlet
w	wall

function the minimization of the entropy generation units by Adaptive Differential Evolution with optional External Archive (JADE) and a novel JADE variant. Kim and Lee [10] numerically investigated the thermal-flow characteristics of PFHE with offset-strip fins for various fin geometries and working fluids, presenting a new correlations, which can be applied to offset-strip fins with blockage ratios greater than 20%. Yang and Li [11] provided a couple of new correlations for general prediction of j and f factors, which excellently correlate a variety of geometrical parameters with blockage ratio ranging from 10% to 60%, based on the analysis of a large amount of numerical data by CFD techniques for offset strip fins.

As is shown above, a lot of researchers focused on the flow and heat transfer characteristics of PFHE. In the meantime, stress analysis, because of complexity of fin structure, especially for serrated fin, was barely to be discussed in documentary. With the development of productivity and the application of new technology and craft, the requirement for loading capability of PFHE is becoming higher and higher, so the solution to optimize geometric structure of PFHE for a higher loading capacity is urgently needed. Ma and Cheng [12] investigated the influence of structure parameters on the stress of plate-fin structures based on finite element method (FEM) and thermal elastic theory for the structural safety of plate-fin structures in actual operation process and the structural design of LNG PFHE. Gong and Jiang [13,14] investigated the effect of nine influence factors on residual stress by presenting a finite element modeling of brazed residual stress in a stainless steel plate-fin structure applied to recuperators in microturbines. In Zhang and Qian's paper [15], the heat transfer, j/f factor, temperature and stress distribution of plate-fin structure were obtained in different fin thickness and fin offset, by the method of experiment, CFD analysis, FSI and FEM. However, it didn't provide the optimal structure based on RS and MOGA.

In this paper, the effects and second order interaction effects of the fin height, fin space, fin thickness and fin interrupted length on heat transfer, flow resistance and stress are analyzed based on FSI, RSM and ANOVA. In addition, in order to guide the design of PFHEs, maximizing the JF factor and minimizing the maximum stress are defined as objectives, while four design parameters are considered as optimization parameters, to get a set of pareto-optimal solutions [16] by implementing MOGA.

2. Geometric structure and numerical model

2.1. Geometric model and boundary condition

Geometric structure of serrated fin is showed in Fig. 1. The boundary conditions of fin channel inlet and outlet are set as velocity inlet and pressure outlet, respectively. The fluid inlet temperature is 300 K and Re is set as 800. On the surface of upper and lower clipboard constant temperature boundary condition (373.15 K) is set for assuming that the cold air is heated by plenty of saturated steam. The periodic boundary condition is applied on both sides of the computational domain. No slip wall and coupled thermal boundary condition are adopted at the interface between fluid and solid. The material of solid domain is set as aluminum and thermal radiation and nature convection are negelected. Air is adopted as working fluid and its property is assumed to be constant. Fig. 1 shows that there is an extension called thermal entry [17], the length of which is calculated according to Eq. (1).

$$L_e = 0.27Re^{0.51}PrD_h \tag{1}$$

To get a constant Re on condition of varying geometric structure, the inlet velocity is set as a variable input parameter, which is calculated according to conservation of mass. The inlet velocitys of different fin structures are calculated by Eqs. (2)–(4) [11] under condition of Re = 800. The laminar model is set for the subsequent calcualtion for the reason that the laminar flow regime is "0 < Re < 1000" for serrated fin channel.