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Sobol sensitivity analysis for governing variables in design of a plate-fin heat exchanger with serrated fins

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A B S T R A C T

Sobol sensitivity analysis can quantify the impact of input parameters' variations on the performance of plate-fin heat exchanger to guide the selection of input variables during design procedure. In this paper, the Reynolds number *Re*, fin height *h*, fin space *s*, fin thickness *t* and interrupted length *l* are considered as five input parameters, while exchanger volume, exchanger material content, heat flow rate and pressure drop with different constraints are taken as the design objectives. Moreover, to study the impact of Prandtl number on input parameters, the Sobol sensitivity indices of five parameters are compared for air and water. The results show that the Reynolds number *Re* and fin space *s* are the two main factors that affect the performance of plate fin heat exchanger. As the heat exchanger size limited, a smaller fin thickness *t* is selectable. Compared with air, the interrupted length *l* should be selected a smaller value for water. Guidance about the fin surface selection is given. Sobol sensitivity analysis methods can be performed to detect the importance of parameters in various complex engineering applications. And compared with other optimization algorithms, this method is simple to implement.

1. Introduction

When the duty requirement (inlet and outlet temperatures and fluid flow rates) and the pressure drop are given, the typical steps for plate-fin heat exchanger (PFHE) thermohydraulic design include the selection of fin type, flow arrangement, the determination of fin configuration, fluid operating that involves the determination of *Re*, the *j* and *f* data acquisition, if any, layer pattern optimization. The exchanger fin type and flow arrangement are firstly selected based on the problem specification and experience. For a PFHE, Hesselgreaves [1] proposed that if heat capacity rate ratio $C^* > 0.25$ ($C^* = C_{min}/C_{max}$), and especially if the required effectiveness $\varepsilon > 0.8$, a counterflow configuration is the most economic design; If $C^* < 0.25$, the flow arrangement configuration makes little difference to the effectiveness, a crossflow design is most appropriate because of its simplicity. The fin surface selection that involves the definition of the fin height *h*, fin thickness *t*, fin space *s*, interrupted length *l* and so on. Under different constrained conditions, the fin surface of PFHEs had been optimized by using different strategies based on genetic algorithm [2–6], imperialist competitive algorithm [7], particle swarm optimization algorithm [8–10], hybrid evolutionary algorithm [11,12] and learning automata based particle swarm optimization [13] for various objectives, such as minimization of total weight, minimization of total annual cost, entropy generation minimization, minimum pressure drop, maximum effectiveness and maximum heat flow rate. However, when it comes to the actual design, the optimized parameters of fin surface to be employed on PFHE design will be a problem because those studies generally apply in specific conditions. Besides, it is difficult for designers to apply those methods to help themselves to select the most beneficial fin surface among the various fin surfaces due to the complexity of those methods application procedures. Therefore, until now, the fin surface is determined mainly based on the empirical chosen but lack the theoretical guidance.

The channel *Re* is closely associated with many factors, such as the pressure drop, heat flow rate, the ratio *j*/*f*, surface efficiency, number of thermal units and hydraulic diameter. That will describe in detail below. The Colburn heat transfer factor *j* and Fanning friction factor *f* were often calculated using the empirical equations. When the air was used as the working media, Kays and London [14], Manson [15], Joshi and Webb [16], Wieting [17], Mochizuki et al. [18], Dubrowsky [19], Manglik and Bergles

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Nomenclature

Latin symbols

α	heat transfer coefficient, W m^{-2} K^{-1}
A	heat transfer area, m^2
A_c	flow area, m^2
c_p	specific heat, J kg^{-1} K^{-1}
D	hydraulic diameter of fin channel, m
$D_i(Y)$	first-order variance
$D_{ij}(Y)$	two-order interaction
$D_{ij\cdots k}(Y)$	high-order interaction
f	friction factor
G	mass velocity, kg m^{-2} s^{-1}
h	fin height, m
j	Colburn factor
l	interrupted length, m
L	length, m
m	mass flow rate
N	number
Nu	Nussle number
NTU	number of thermal unit
Δp	pressure drop, Pa
Pr	Prandtl number
Q	total rate of heat transfer, W
Re	Reynolds number
s	fin space, m
S_i	first-order sensitivity index
S_{ij}	two-order sensitivity index
$S_{ij\cdots k}(Y)$	high-order sensitivity index
S_{Ti}	total sensitivity index
T	temperature, K
t	fin thickness, m
u	velocity, m s^{-1}
U	total heat transfer coefficient, W m^{-2} K^{-1}
V	volume, m^3
V_m	material content, kg
Var(Y)	total variance of the output goals
X	parameters
Y	target function

Greek symbols

δ	thickness of cover plate, m
ρ	density, kg m^{-3}
μ	viscosity, kg m^{-1} s^{-1}
λ	thermal conductivity, W m^{-1} K^{-1}
ε	effectiveness
η	efficiency
σ	porous ratio

Subscripts

c	cold side
h	hot side
H	height
i	inlet
L	length
o	outlet
w	wall
W	width

[20] and Yang and Li [21] had provided different empirical correlations for PFHEs with serrated fins based on experimental data or based on numerically investigated by Kim and Lee [22]. But, for high Prandtl fluid, using those empirical equations to calculate the j and f factors might produce large errors because those empirical equations are generally greatly affected by the type of working media. According to the research of Hu and Herold [23], for water and ethylene glycol, the value of the experimental j factor was approximately twice as big as the value of the empirical equation. Unfortunately, there is scarce data for the high Prandtl fluid. Finally, layer pattern optimization is needless or eases when the heat transfer occurs among few fluids.

Sensitivity analysis is capable to quantify the relative importance of design parameters in determining the value of an assigned output objective function. Thus, the most influential parameters and weak impact parameters from a set of parameters can be determined by using the sensitivity analysis. The sensitivity analysis method mainly includes differential method, regression method, screen method, variance based method and so on. The differential method only explores a reduced space of the input factor around a base case, and the regression method is only suitable for linear models or monotonic functions. The screen method only provide qualitative the effects of different factors on outputs. Compared with the above-mentioned methods, the variance based method can quantify the effects of different factors, confirms the interactions between factors and is suitable for nonlinear and non-additive models, etc. The drawback of this approach is its high computational expensive. More detailed information about the advantages and disadvantages of these methods can be found in the literature [24]. Lerou et al. [25] and Wen et al. [26] optimized the geometry of PFHEs using one-factor-at-a-time methods. Kotcioglu et al. [27] reported optimum values of design parameters in a heat exchanger with a rectangular duct by Taguchi method. Fesanghary et al. [28] explored the use of global sensitivity analysis and harmony search algorithm for design optimization of shell and tube heat exchangers. Qi et al. [29] studied five experimental factors affecting the heat transfer and pressure drop of a heat exchanger with corrugated louvered fins using the Taguchi method. Detecting effects of design parameters can greatly reduce parameter uncertainties and increase the model accuracy. In practice, sensitivity analysis is very suitable for engineering applications because it is characterized by simple to implement, easy to interpret and low computational cost. However, few researches about the sensitivity analysis of PFHE with serrated fin have been published.

The aim of the present paper is to quantitatively evaluate the effects of different parameters to guide the design of PFHE with serrated fins. Therefore, Sobol sensitivity analysis was applied to study the effects of Re, fin height h, fin space s, fin thickness t and interrupted length l on the performance of PFHE. Besides, in order to study the Prandtl number effect, the effects of different parameters on the objective functions were studied for air and water as the working media, separately.

2. Design methodology and Sobol method

2.1. Thermohydraulic model

In this section, the equations for calculating heat exchanger volume and material content are presented for fixed heat flow rate and pressure drop in a counter flow PFHE. Moreover, the equations of the heat flow rate and pressure drop are also shown for fixed heat exchanger size. To better study the sensitivity of different parameters on the objective functions, the configuration parame-