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Multi-objective optimization of geometrical parameters of corrugated-undulated heat transfer surfaces

Limin Wang [a], Lei Deng [a], Chenglong Ji [a], Erkai Liang [b], Changxia Wang [b], Defu Che [a,*]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] Harbin Boiler Preheater Co., Ltd., Harbin Electric Corporation, Harbin 150046, PR China

HIGHLIGHTS

- The effects of geometrical parameters of different CU passages were studied.
- SVMs were trained to predict the performance of CU heat transfer elements.
- Evaluation criteria suitable for plate heat transfer elements were proposed.
- The CFD, SVM and GA was applied jointly to the optimization of CU passages.
- The method was proved efficient to optimize plate heat transfer elements.

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ABSTRACT

To achieve a maximum heat transfer capability and a minimum pumping power for corrugated-undulated (CU) heat transfer surfaces, a multi-objectives genetic algorithm was used to obtain the optimal values of the pitch and height of undulated plate (U-plate) and the height of the corrugated plate (C-plate) by using the Pareto optimal strategy. For this purpose, computational fluid dynamics (CFD) simulation, support vector machine (SVM) and the fast non-dominated sorting genetic algorithm were combined together and used for the optimization process. Three dimensional numerical simulations were performed to investigate the effect of geometrical parameters on the thermos-hydraulic performance of CU heat transfer surface. The maximum deviation for the Nusselt number and friction factor between the simulation and the published data were 8.81% and 13.1% respectively when the Reynolds number ranged from 1500 to 10,000. The flow and temperature profile in the CU passage were analyzed. Intensive secondary flows occurred in the C-plate channel and the U-plate channel due to the drag effect between the main flows in the two channels. And the effects of Reynolds number and structure parameters were studied. The change of U-plate height rather than that of U-plate pitch would have a dominant effect on the disturbance influence of U-plate. Besides, two SVM models were trained by the CFD results to predict the Nusselt number and friction factor of flow in CU passages with different geometrical and operational parameters. The comparison between the SVM predictions and the CFD results showed that the SVM models could predict the numerical data with a good accuracy. In addition, two evaluation criteria were proposed from perspectives of the manufacturers and the users, respectively. Finally, a set of optimized solutions were obtained. The optimal values of pumping power ratio and heat transfer area ratio between different CU passages and the standard one were in the range of 0.8–3.1 and 0.5–1.2, respectively. The manufacturers and the users can select the best design points according to their considerations.

1. Introduction

Energy conservation has been a great concern in the present time all around the world. The efficiency improvement of the energy-conversion device including large fossil-fuel-fired boiler has been challenging scientists and engineers. Rotary air heaters have been employed extensively in power stations for the final recovery of heat from the combustion products due to their compactness and superior performance. The performance of an air preheater mainly depends on the geometrical design of the heat transfer elements. Many investigations have been performed on

* Corresponding author.
E-mail addresses: dfche@mail.xjtu.edu.cn, dfche.xjtu@gmail.com (D. Che).

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Nomenclature

A	cross-section area of a regenerator, mm^2
A_{fr}	effective flow area, mm^2
A_n	cross-section area of a CU passage, mm^2
D_h	hydraulic diameter, mm
E_F	Evaluation criteria for heat transfer area
E_P	Evaluation criteria for pumping power
f	friction factor
F	heat transfer surface area of a regenerator, mm^2
G	mass flow cross the unitary cell, $kg\,s^{-1}$
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
H	wave height of the plate, mm
L	length of the regenerator, mm
m	fluid mass flow rate, $kg\,s^{-1}$
Nu	Nusselt number
p	static pressure, Pa
P	wave pitch of the plate, mm; pumping power, W
Δp	pressure drop, Pa
Pr	Prandtl number
q	heat flux, $W\,m^{-2}$
Re	Reynolds number
S_d	developed area of a unitary cell, mm^2
T	temperature, K
V	volume of a unitary cell, mm^3

Greek symbols

δ	thickness of the plate, mm
φ	porosity of a plate heat transfer element
μ	dynamic viscosity, Pa s
θ	angle of inclination, °
ρ	fluid density $kg\,m^{-3}$
σ	heat transfer area density of a plate heat transfer element, m^{-1}

Subscripts

C	C plate
U	U plate
0	a standard heat transfer element
W	wall of a unitary cell

how to improve the thermal–hydraulic performance of the heat transfer elements.

The corrugate-undulated (CU) surfaces, as shown in Fig. 1, are widely used in air preheaters and micro-turbine regenerators. Corrugated-undulated geometry could be considered as a general type of the crossed-corrugated (CC) geometry [1]. Besides, the local structures in many other heat transfer elements are same as the CU surfaces. Therefore, it is of great importance to study the thermo-hydraulic performance of CU heat transfer surfaces.

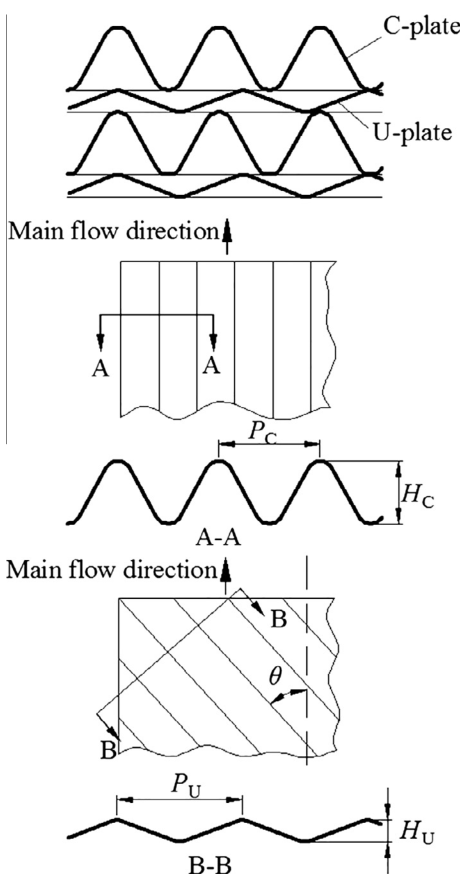

Fig. 1. A general view of a corrugated-undulated heat transfer surfaces.

Many investigators have conducted experiment to study the effect of geometrical parameters on the thermo-hydraulic performance of plate heat transfer elements [1–6]. Focke and Knibbe [2], and Luna et al. [3] studied the complex flow patterns in CC passages by using visualization techniques. Fock et al. [4] studied the influence of geometric parameters of CC passages on the heat transfer coefficient and pressure drop. Stasiek et al. [5] measured local Nusselt number (Nu_L) in corrugated passages by employing liquid crystal thermography. It is quite costly to conduct detailed measurements of velocity and temperature fields, because the flow passages among plate heat transfer surfaces are of small dimensions and very complex geometrically. Therefore, many researchers have performed computational fluid dynamics (CFD) simulation by focusing their computational domain on one or several unitary cells [7–9]. Ciofalo et al. [7,8] employed one laminar and four turbulence models to simulate fluid flow and heat transfer in corrugated passages. Blomerius et al. [9] numerically investigated the flow field and heat transfer in CC ducts under laminar and transitional flow regimes. Fernandes et al. [10] predicted the performance of CC plates with fully developed laminar flow by conducting numerical simulations within seven consecutive unitary cells along the main flow direction. Zhang and Che [11] numerically researched the influence of corrugation profiles on their thermos-hydraulic performance. However, most of research on the plate heat transfer elements was just focus on the effects of different structure parameters. To our knowledge, there is no study on the optimization of the parameters of the CU passages.

The main factors affecting the performance of heat exchangers are: (1) heat duty increase or area reduction, (2) initial cost and (3) pumping power or operating cost. As the relations of these factors with the geometrical parameters of the plate heat transfer surface are complex, it is difficult to quantify them together. There are numerous performance evaluation criteria (PEC) to describe and assess the performance of a heat exchanger. The ratios j/j_s and f/f_s, where the subscript s is for a smooth surface for the same Re, have been used to quantify the performance improvement. Because actual performance may be subject to specific operating constraints, this performance evaluation method is not recommended [12]. The ratio j/f was used by Kays and London [13] to