Multi-Objective Optimization of A PCHE Channels

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1. Introduction

High-temperature, gas-cooled nuclear reactors with a closed gas turbine cycle are recently being considered as a nuclear power generation concept for the future. In theory, the gas turbine cycle has an advantage in terms of simplicity and efficiency compared to the steam turbine cycle [1]. However, since gas is used as the working fluid, inefficiency due to large volumes is inevitable, and a heat exchanger is used as a recuperator and pre-cooler. To solve this problem, different types of heat exchanger are needed. One of the alternative heat exchangers is the printed circuit heat exchanger (PCHE) developed by HEATRIC [2]. Each flow channel of the PCHE is made through chemical etching on the surface of metal plates, and the typical PCHE channels on each plate have a zigzag shape to promote the heat transfer between the cold and hot channels.

In this work, the zigzag flow channels of the PCHE have been optimized by using three-dimensional RANS analysis and a hybrid multi-objective evolutionary algorithm [3] coupled with the RSA model [4]. The cold channel angle and the ellipse aspect ratio of the cold channel are employed as the design variables. A group of optimal shapes are presented through Pareto-optimal front (POF) by an ε-constraint strategy through an NSGA-II algorithm.

2. Flow Analysis and Optimization Methods

The present computational analyses were performed with the commercial CFD code, ANSYS CFX-11.0 [5], which employs an unstructured grid to solve governing equations for three-dimensional steady turbulent flow and heat transfer in the PCHE. The working fluid used in this calculation is supercritical carbon-dioxide, and the Reynolds number based on the hydraulic diameter of the channel is 152,000. The Shear Stress Transport (SST) model [6] with automatic wall treatment is used for predicting turbulent flows in the zigzag PCHE channel.

As shown in Fig. 1, the entire computational domain consists of cold channels, hot channels, and a steel substrate. Convective heat transfer in the cold and hot channels and heat conduction in the substrate are analyzed in present work. Periodic conditions are used on the upper and lower boundaries and on each side boundary. And, each domain is connected to the other domain using a domain interface condition with GGI [5] in the numerical analysis.

In the first step of the optimization procedure, the objective function and design variables are chosen. The design space is then decided from a parametric study for improved system performance. Experimental points are selected through the design of experiments. At these experimental points, the objective function values are calculated using RANS analysis. Finally, the RSA model is constructed, and the Pareto optimal solutions are sought by a multi-objective evolutionary algorithm.

The friction factor in the cold channel of the PCHE (F_p) and the effectiveness of the PCHE (F_{eff}) are used as objective functions. The purpose of the optimization is to minimize F_p as well as maximize F_{eff}. F_p and F_{eff} are defined as follow.

$$F_p = \frac{p_{inlet} - p_{outlet}}{0.5 \rho_{avg} v_{avg}^{\ 2}} \tag{1}$$

$$F_{eff} = \frac{T_{hot,in} - T_{hot,out}}{T_{hot,in} - T_{cold,in}} \tag{2}$$

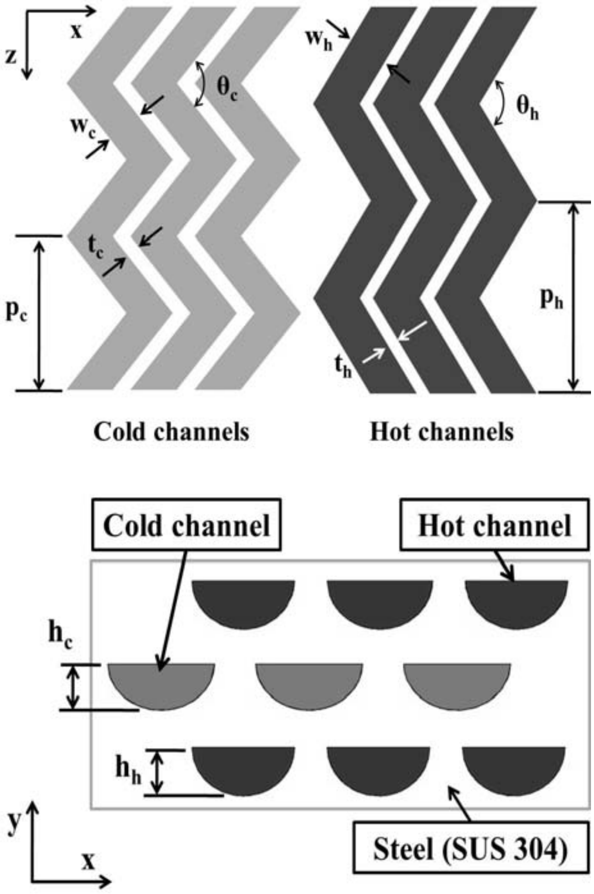

Fig. 1 Geometry of the channels in the zigzag PCHE [7]

Table I: Results of optimization

Cluster	Design variable		Objective function			
			MOEA prediction		RANS	
	θ_c	$w_c/2h_c$	F_{eff}	F_p	F_{eff}	F_p
A	98	1.57	0.5038	30.43	0.4953	25.98
B	164	1.29	0.3840	0.4984	0.3852	1.804
Reference	100	1.00	-	-	0.4881	19.88

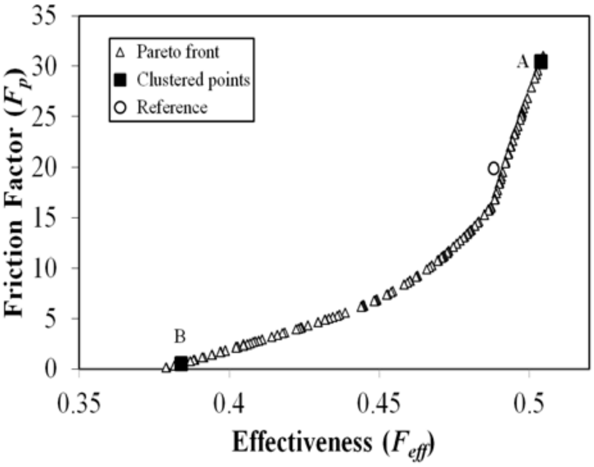

Fig. 2. Pareto optimal front by hybrid MOEA

The cold channel angle (θ_c) and ellipse aspect ratio of the cold channel ($w_c/2h_c$) are employed as non-dimensional design variables. These variables are represented in Fig.1.

3. Results

Fig. 2 shows the POF that is generated by the hybrid MOEA through the RSA model. Here, it can be noticed that no solution out of these Pareto optimal solutions is superior to any other in both objectives since each solution is a global Pareto optimal solution. The two cluster points from the hybrid MOEA (Design A and Design B) are selected through K-means clustering. Design A shows a high pressure drop and high effectiveness. On the other hand, Design E represents a low pressure drop and low effectiveness. Hence, designers can select any optimum design from the POF according to their needs.

Two optimal designs clustered from POF and their objective function values are shown in Table I. Under Design A, F_{eff} is increased by 1.48 %, and F_p is also increased by 30.7 %, in comparison with the reference geometry. On the other hand, under Design B, F_{eff} and F_p are reduced by 21.1 % and 90.9 %, respectively.

4. Conclusions

Zigzag PCHE channels have been optimized with the help of the RSA surrogate model and a genetic algorithm with three-dimensional RANS analysis. The cold channel angle and the ellipse aspect ratio of the cold channel are employed as design variables for the optimization. And, two objective functions, viz., the effectiveness of the PCHE channels and the friction factor of the cold channel, are defined. the Pareto-optimal front (POF) has been obtained by the hybrid MOEA. Two Pareto-optimal designs, namely, Design A and Design B, which are located at opposite extremes of the POF, have shown improved performances in effectiveness and pressure drop, respectively .

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