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Shape optimization of inlet part of a printed circuit heat exchanger using surrogate modeling

Gyoung-Wan Koo, Sang-Moon Lee, Kwang-Yong Kim*

Department of Mechanical Engineering, Inha University, Incheon 402-751, Republic of Korea

HIGHLIGHTS

- Shape optimization of inlet part of a PCHE was performed using 3-D RANS analysis and surrogate modeling.
- Objective function is weighted sum of the objectives related to flow uniformity (F_f) and pressure drop (F_P).
- Objective function was reduced by 1.36 and 1.18%, respectively, by the RBNN and KRG compared to reference.
- F_f was increased by 7.5% while F_P was decreased by 7.6% by KRG compared to reference.
- Errors between objective function values predicted by surrogates and RANS analysis were only about 3.0%.

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ABSTRACT

Aim of the present work is to optimize the shape of inlet part of a printed circuit heat exchanger to enhance the thermal–hydraulic performance using surrogate modeling. The fluid flow was analyzed using three-dimensional Reynolds-averaged Navier–Stokes analysis with the shear stress transport turbulence model. The non-dimensional parameters related to the angle and radius of curvature of the inlet plenum wall, and diameter of the inlet pipes were selected as design variables for the optimization. The objective function was defined as a weighted-sum of two objectives related to uniformity of the mass flow rate distribution and pressure loss, respectively. Twenty six design points were obtained by Latin hypercube sampling method. The Kriging and the radial basis neural networks were used as surrogate models to approximate the value of the objective function. The results of the optimization with a weighting factor show that the objective function values of the optimum designs obtained by the two surrogate models were similar to each other and improved from that of the reference design.

1. Introduction

Recently, the gas turbine cycle, which has the advantages such as simplicity and efficiency in comparison with the steam turbine cycle, has been considered as a potential nuclear power generation for the future. However, the harsh environment of gas turbine cycle, such as high temperature and pressure, may cause the instability of the system operation. Furthermore, the inefficiency due to the large volume is inevitable since gas is used as a working fluid. Printed circuit heat exchanger (PCHE), which is suitable for the gas turbine cycle due to high pressure resistance and compactness, was developed by HEATRIC [1] in order to overcome these operating conditions. Actually, PCHEs are smaller and lighter than cell & tube type heat exchangers which have similar performance. On the other hand, PCHEs are made through chemical etching and diffusion bonding. Therefore, operation of PCHEs is more stable and effective than the other types of heat exchanger. Fig. 1 [2] shows the outline of the inlet part of the PCHE. As shown in this figure, the main stream is distributed to branch channels through the inlet plenum.

During the last decade, many research works have been performed on PCHEs both experimentally and numerically. Mostly these studies were performed for geometry construction with zigzag channels and proper operating conditions of PCHE. Ishizuka et al. [3] analyzed the characteristics of a PCHE in terms of the thermal performance and pressure drop of supercritical carbon-dioxide (CO_2) in the PCHE under variations of the flow rate, pressure, and temperature. Ngo et al. [4] performed numerical analysis to compare the performance of a PCHE channel with an S-shaped fin with that of a reference PCHE channel using three-dimensional Reynolds-averaged Navier–Stokes (3-D RANS) analysis. Nikitin

* Corresponding author. Department of Mechanical Engineering, Inha University, 253 Yonghyun-Dong, Nam-Gu, Incheon 402-751, Republic of Korea. Tel.: +82 32 872 3096; fax: +82 32 868 1716.
E-mail address: kykim@inha.ac.kr (K.-Y. Kim).

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et al. [5] obtained the thermal–hydraulic characteristics of a PCHE in an experiment with a supercritical carbon-dioxide loop. Kim et al. [6] performed a comparative study on zigzag and airfoil-shaped fin PCHEs using 3-D numerical analysis. They showed that the airfoil-shaped fin PCHE had almost the same total heat transfer rate per unit volume and decreased pressure drop compared with the zigzag PCHE. Kim et al. [7] performed a numerical study on the flow characteristics and thermal performances of PCHEs using RANS analysis. Lee et al. [8] performed a multi-objective optimization to enhance the heat transfer performance and to reduce the pressure drop in zigzag channels of a PCHE with three geometrical parameters. Many researches have been performed on the flow and heat transfer in the channels of PCHEs, but only focused on the zigzag part of the PCHE channels. However, the inlet plenum of the PCHE is also important, because high pressure loss and non-uniformity in the mass flow distribution may occur in this inlet region.

On the other hands, the optimization technique combined with RANS analysis has been widely adopted in the field of engineering application. Kim and Kim [9] performed optimization of a vane diffuser in a mixed-flow pump to improve the efficiency using optimization technique. And, they obtained the result that the efficiency at the design flow coefficient was improved by 7.05% and the off-design efficiencies were also improved in comparison with the reference design. Kim and Kim [10] obtained the optimum shape of 3-D channel roughened by angled ribs using optimization technique with RANS analysis. They reported that optimal values of rib pitch-to-rib height ratio and rib displacement-to-rib height ratio increase, but those of attack angle and rib height-to-channel height ratio decrease as design emphasis was shifted to reduction of friction loss. Husain and Kim [11] performed an optimization of a rectangular micro-channel heat sink for minimum thermal resistance using surrogate models. They founded that thermal resistance of the heat sink was more sensitive to channel width-to-depth ratio than fin width-to-depth ratio around the optimal point. Raza and Kim [12] carried out a shape optimization of a wire-wrapped fuel assembly using Kriging meta-modeling technique. They defined the objective function as a linear combination of heat transfer and friction loss related terms with a weighing factor.

Recently, Lee et al. [13] performed a parametric study on inlet part of a PCHE, where the effects of geometric variables on hydraulic performance of the PCHE have been tested numerically. In the present work, the inlet part of the PCHE was optimized using surrogate-based optimization techniques with three non-dimensional design variables related to the angle and radius of curvature of the inlet plenum wall, and diameter of the inlet pipes, respectively. For the optimization, numerical analysis was performed in the inlet part of the PCHE using 3-D RANS. The Kriging (KRG) [14] and radial basis neural networks (RBNN) [15] models were used as the surrogate models to approximate the objective functions for the optimization. Twenty-six experimental points in design space were chosen by Latin Hypercube Sampling (LHS) [16] for the three design variables.

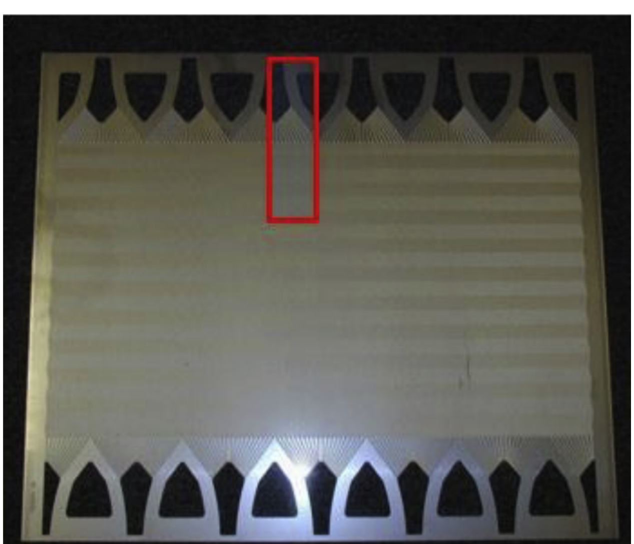

Fig. 1. Example of full size platelet [2].

2. Numerical analysis

3-D RANS analyses of the fluid flow and convective heat transfer were conducted by using ANSYS-CFX 11.0 [17]. The solutions were obtained by solving the compressible RANS equations through the finite-volume method to discretize the governing differential equations in the inlet part of PCHE. Shear stress transport (SST) model [18] was employed as turbulence closure. SST model combines the advantages of the $k-\varepsilon$ and $k-\omega$ models with a blending function. The $k-\omega$ is activated in the near-wall region, and the $k-\varepsilon$ is used in the region far from the wall. Bardina et al. [19] reported that the SST model efficiently captures separation under an adverse pressure gradient compared to the other eddy viscosity models.

Fig. 2 shows the reference geometry of the inlet part of PCHE constructed based on the experimental work of Ishizuka et al. [3]. This inlet part consists of three sub-parts, namely, zigzag channels, inlet pipes, and inlet plenum. And, the dimensions of reference geometry of PCHE are given in Table 1. The boundary conditions and physical properties, which were used for numerical analysis of inlet part of PCHE, are listed in Table 2 based on the experimental work of Ishizuka et al. [3]. An example of grid system in the calculation domain is shown in Fig. 3. To construct the volume meshes, unstructured tetrahedral meshes were employed in most of the domain, and the prism meshes were used near the walls. High resolution scheme was selected for discretizing the governing equations.

A turbulence intensity of 5% and an auto-computed length scale were selected for the inlet turbulence conditions. The first grid points adjacent to the walls are placed at $y+$ less than 1.0, which is required to implement the low-Reynolds-number SST model. A residual reduction factor of 10^{-6} was used for the convergence of the iterative solutions. A personal computer with an Intel core I7 2.4 GHz CPU was used for the computations, and the total time for getting each converged solution was in the range of 20–23 h.

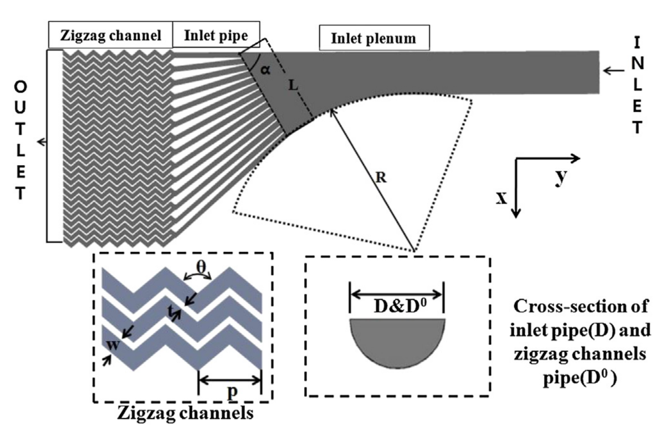

Fig. 2. Geometry of the inlet part in the PCHE.

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