Optimization Investigation on Wavy Channel Printed Circuit Heat Exchanger for Solar Energy Powered Brayton Cycle

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Abstract. The Printed Circuit Heat Exchanger(PCHE) has received widely attention for their high effectiveness and compact size and they appear promising to be employed as the heat exchanger in solar thermal system. In this research, the thermal and hydraulic performance of the wavy channels for solar energy were investigated detailed in different amplitudes, inclined angles and channel diameters. The three-dimensional numerical analysis was performed by computational fluid dynamics(CFD) tool and the model is validated by comparing with previous experimental data. Besides, it was difficult to get the universal correlations of Nusselt number and friction factor for various geometrical parameters. In this article, the Krigeing response surface method is applied to predict the friction factor and j factor for PCHE wavy channels in different geometrical parameters based on the CFD simulation results. The thermal-hydraulic characters predicted by Krigeing response surface showed overall good agreement with the CFD results. Moreover, one of the most popular multi-objective genetic algorithms NSGA-II was adopted in optimization, to maximize j factor, while minimize the fanning friction factor.

Keywords: solar thermal system; printed circuit heat exchanger(PCHE); wavy channels; Krigeing response surface; non-dominated sorting genetic algorithms (NSGA-II)

1. Introduction
The global energy demand dramatic increase while the fossil resource is keeping in continuous consumption. Solar and other new clean energy are all expected alternatives to replace the conventional fossil resource. In the past three decades, large studies around the applications of solar energy have been done especially for the solar energy power for electricity generation and heat collection/refrigeration thermal cycle. Yamaguchi et al.[1, 2] proposed a solar energy powered Rankine cycle for combined heat and power. Their designed and constructed an experimental prototype in Kyoto, Japan, the experimental results showed that the solar energy powered Rankine cycle using CO₂ operate stably with electricity and heat generated. Fahad et al.[3] conducted five different SCO₂ Brayton cycles based on solar power tower and they found that the recompression cycle has the highest thermal efficiency. Pardeep et al.[4] investigate the SCO₂ Brayton cycle for possible concentrated solar power applications and compared it with trans- and sub-critical operations of the same fluid for thermal efficiency, specific work output and magnitude of irreversibility generation. The results show that the SCO₂ Brayton cycle has a comparatively better performance. Francesco et al.[5] reviewed all the works published in the SCO₂ cycle including the cycle powered by solar energy.

The PCHEs are more and more popular in many areas, including nuclear energy, electronic cooling and ocean engineering. Compared with the conventional shell and tube heat exchanger, the PCHEs can...
reduce 85% weight and only take place one third room. Besides, the diffusion bonding technique allows the PCHEs enduring a wide range of temperature and pressure. Due to plenty of advantages, researchers pay much attentions on PCHE and make abundant studies around the thermal-hydraulic performance. Justin et al. have investigated the thermal and hydraulic performance for straight channel PCHEs in Very High Temperature Reactors (VHTRs). Ting Ma et al.[6] identifies the local thermal-hydraulic performance of zigzag channel PCHE at high temperature of 900℃. Jeon et al.[7] outlined an innovative type of PCHE, considered the effect of channel sizes, the spacing between channels and the channel cross-sectional shape on the thermal-hydraulic performance. Aneesh et al.[8] clarified the heat transfer rate and thermo-hydraulic performance of trapezoidal, sinusoidal and triangular channel PCHE. The helium test loop and numerical simulations were conducted by In Hun Kim et al.[9], they obtained the fanning-friction factor and Nusselt number correlations with the operation condition parameters. The academic community has extensively explored the thermal performance for solar Brayton cycle with SCO2. However, little research has been conducted of the recuperators. The study explores thermal-hydraulic performance of sinusoidal channel PCHE used in solar Brayton cycle. We then model and optimize the recuperators with the goals of minimizing the friction factor and maximizing the j factor.

2. Calculation model and numerical method

2.1. System description
The schematic of SCO2 Brayton cycle is shown as figure 1. The important components are turbine, compressor, recuperator, air cooled pre-cooler and receiver. The receiver absorbs the concentrated solar energy to heat the fluid, the hot fluid goes through the turbine and then the hot fluid heats the cold fluid from the compressor in the recuperator which consists of several channels and multiple plates.

![Figure 1. Schematic of solar energy powered SCO2 Brayton cycle](image)

2.2. Calculation model
The PCHE system as illustrated in figure 2 right contains a stack of photochemical etching planets with many semicircular fluid passages. The sinusoidal channel PCHEs are investigated and the reduced models are used in three-dimensional simulations. In this work, the radium of the hot channel \( R_h \) and cold channel \( R_c \) change from 0.5mm to 1.5mm, the pitch length \( L_p \) ranges from 10mm to 30mm and the angle \( \alpha \) varies from 5° to 45° as illustrated in figure 2 left. The cold and hot SCO2 are utilized as the working fluid, the inlet temperature and the outlet pressure in cold fluid are set as 450K and 20MPa, while those in hot fluid are set as 630K and 7.4MPa respectively. The ANSYS FLUENT is used to numerical simulate the PCHEs and the finite volume method is taken to describe the governing equations. The RNG k-\( \varepsilon \) model is adopted for modelling the
Figure 2. The configuration of PCHE

turbulence. The mass flow inlet and pressure outlet boundary conditions are specified on the cold channel and hot channel correspondingly. The periodic boundary condition is applied on the up and down walls and the adiabatic boundary condition is set for the front, back walls and side walls. The NIST real gas model is applied to estimate the thermal properties of the SCO2. The thermal-hydraulic characteristic considered include the heat transfer coefficient, Nusselt number and fanning friction factor as illustrated in equations (1–4). The \( j \) factor is shown in equation (5).

The hydraulic diameter of the channel is

\[
D_h = \frac{\pi R}{(\pi / 2 + 1)}
\]

where the \( R \) is the channel diameter. The heat transfer coefficient is described as followed

\[
h = \frac{q}{T_b - T_w}
\]

where the \( T_b \) is the volume average temperature of fluid, \( T_w \) is the area weighted temperature of the channel walls. The Nusselt number is shown as followed

\[
Nu = \frac{hD_h}{\lambda}
\]

where the \( \lambda \) is the heat conductivity of fluid. The fanning friction factor is expressed as followed

\[
f = \frac{\Delta p \cdot D_h}{2 \rho L u_{in}^2}
\]

where the \( \Delta p \) is the pressure different between the inlet and outlet, \( \rho \) is the fluid density, \( L \) is the total length of channels and the \( u_{in} \) is the inlet velocity. The \( j \) factor is expressed as followed

\[
j = \frac{D_h}{4L} \rho^{2/3} N
\]

where the \( N \) is the heat transfer units number of the whole PCHE.

3. Optimization methods

In this study, the Kriging response surface and multi-objective genetic algorithm NSGA-II are combined to optimize the wavy PCHEs. As for the recuperators, the thermal and hydraulic performance should be considered. The geometric parameters include the radium of cold and hot channel, the width and height of single unit, the length of single pitch and the angle of the wavy PCHE.

3.1. Kriging response surface and Non-dominated Sorted Genetic Algorithm-II

The Kriging response surface is a spatially optimal linear unbiased estimation method based on the spatial distribution of spatial attributes. The semi-variogram is used to determine the weights of the points to be interpolated in order to realize the estimation of the attributes of the points to be interpolated. The method takes into account the spatial structure and randomness of the variables and statistics by simulating the correlation and variability of the spatial distribution of geographical
phenomena. The Kriging response surface provide an approximation of the input parameters of the values of objectives, which allows a faster optimization operation. Firstly, only limited cases selected by space-filling designs should be calculated of three dimensions to fit the model. Secondly, during the optimization the population is simulated by the Kriging models. Therefore, the Kriging response surface is used as the surrogate model based on the simulation results in this paper.

Over the past decade, plenty of multi-objective evolutionary algorithms (MOEAs) have been proposed. The MOEAs should find multiple Pareto-optimal solutions in a single simulation run, and the NSGA is the first algorithm achieving the goal. However, the NSGA algorithm has high computational complexity, lacks elitism, needs the user to specify sharing parameters. To overcome those weak points, the improved algorithm NSGA-II was proposed by Kalyanmoy et al.

3.2. Objective functions and design parameters

In this study, the $j$ factor and the fanning friction factor were considered as the objective functions. Besides, the geometric parameters such as the incline degree, the pitch length, the radium of channel, the height and the width were set as the design parameters. The Kriging metamodel fit was created by using one hundred design points which were generated by Latin Hypercube sampling. Latin hypercube and randomly selects survey units without any grouping, classification and queueing. Each unit of the sample is completely independent, and there is no certain correlation between them.

4. Results and discussions

4.1. Sensitivity analysis of thermal and hydraulic performance

The effects of the radium on the two channels, the inclined angle and the pitch length on the fanning friction factor and the $j$ factor are shown in figure 3. In this section, the radium of cold/hot channel ranges from 1.5mm to 0.5mm in step of 0.1mm, the inclined angle ranges from 45° to 5° in step of 4°, the pitch length ranges from 30mm to 10mm in step of 2mm.

Figure 3(a) shows the effects of the design parameters on the fanning friction factor. The results prove that the cold fluid fanning friction factor decrease with all the variables except the inclined angle. It is obvious that the bigger the radium is the lower the velocity is, so that the pressure drop is relatively lower and the fanning friction factor declines. The pressure drop is much bigger with a longer channel, while the pressure drop will be bigger when the inclined angle increase.

The effects of design variables on the $j$ factor is shown in figure 3(b). The results reveal that the $j$ factor increases with the radium of hot channels. The cases with smaller hot channel has a larger Nusselt number but a much larger Prandtl number, which causes a higher $j$ factor. However, the $j$ factor decreases with the decrease of the inclined angle and the pitch length which because of the lower heat transfer coefficient. The $j$ factor decreases with the radium of cold fluid declining. The smaller cold channel leads to higher heat transfer coefficient, but the influence of the radium reduction on the Nusselt number dominants.

As indicated in figure 3(c), the trends of hot fluid fanning friction factor are similar to the cold one. The radium of channels and the pitch length tend to decrease the fanning friction factor because of the lower pressure drop.

Regard of the $j$ factor of hot fluid, the trends of hot fluid fanning friction factor expect that of the radium of hot channel are almost similar to the cold one as shown in figure 3(d). The $j$ factor decreases with the decrease of the inclined angle and the pitch length which because of the lower heat transfer coefficient. The $j$ factor decreases with the radium of cold fluid declining because the reduction of Nusselt number. However, the $j$ factor decreases first and then increases with the radium of hot channel. It is observed that the Prandtl number and the Nusselt number both increase with the radium of hot channel, but the Prandtl number increasement is more rapid first. In addition, the values of the hot fluid $j$ factor are a little higher that the cold fluid $j$ factor.

4.2. Optimization results

In this section, multi-objective optimization using NSGA-II is conducted to trade-off between the fanning friction factor and the $j$ factor for them are mutually conflicting where no single solution can
fully satisfy together. In fact, a set of design points displayed as a Pareto optimal solutions curve will be selected. figure 4 shows the results of Pareto optimal curve with the corresponding design parameters. It is obvious that the fanning friction factor increases with the j factor. Moreover, ten of the selected optimal parameters with a less fanning friction factor and a higher j factor are shown in table 1. From the table, it can receive that the radium tends to the two extremes of 1.5mm and 0.5mm, the larger inclined angle prefers a smaller pitch length.

![Figure 3](image1)

**Figure 3.** The effect of radium of hot channel, the radium of cold channel, the inclined angle and the pitch length on (a)fanning friction factor of cold fluid (b) j factor of cold fluid (c) fanning friction factor of hot fluid (d) j factor of hot fluid

5. Conclusions
In this paper, the Kriging response surface and the Non-dominated Sorted Genetic Algorithm-II were combined for the optimization of wavy channel PCHEs. The main conclusions are listed as below:

1. The sensitivity analysis of the objective functions with respect to the design parameters are analyzed from qualitative to qualitative which is significant to guide the wavy channel PCHEs of the Brayton cycle powered by solar energy.
2. The obtained Pareto optimal points reveal that the radium tends to the two extremes of 1.5mm and 0.5mm, the larger inclined angle prefers a smaller pitch length.
Figure 4. Pareto optimal curve of fanning friction factor and $j$ factor

| Points | $R_h$/mm | $R_c$/mm | $\alpha$/° | $L_p$/mm | $f$   | $j$   |
|--------|----------|----------|-------------|----------|-------|-------|
| A      | 1.50     | 0.55     | 7.96        | 28.73    | 0.0043| 0.0041|
| B      | 1.38     | 0.66     | 12.77       | 19.69    | 0.0086| 0.0051|
| C      | 0.50     | 1.23     | 38.80       | 10.30    | 0.0180| 0.0052|
| D      | 0.50     | 1.41     | 42.25       | 12.0     | 0.0262| 0.0065|
| E      | 0.5      | 1.49     | 44.11       | 11.95    | 0.0372| 0.0072|
| F      | 1.5      | 1.5      | 45          | 10       | 0.0468| 0.00746|

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