Thermal stress analysis of printed circuit heat exchanger based on thermal-structural coupling method

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Abstract. The supercritical carbon dioxide (S-CO\textsubscript{2}) Brayton cycle has the advantages of high efficiency, compactness and simplicity. It is expected to become the main technical route for the future advanced ship nuclear power platform. The printed circuit heat exchanger (PCHE) with ultra-high pressure, ultra-compact and ultra-high efficiency typical characteristics is the ideal configuration of the S-CO\textsubscript{2} power generation system recuperator. The PCHE numerical analysis model is constructed and the thermal stress field of the PCHE core structure is analyzed by thermal-structural coupling method. The results show that the maximum thermal stress of the PCHE core structure is 117 MPa, which is less than the yield limit of the material and meets the requirement of strength safety. The thermal stress value of most regions in PCHE is less than 78.2MPa. Therefore, the current design scheme has a large safety margin. The PCHE compactness can be further improved by structural parameter optimization.

1. Introduction
Limited to narrow spaces and complex working environments, ship nuclear power platforms impose stringent design requirements for heat exchangers with high efficiency, compactness, high reliability and low vibration. The PCHE has a fine passage of 0.5 mm to 4 mm. Under the same exchanging heat quantity, the weight and volume of the PCHE are only 1/5 and 1/8 of the conventional shell-and-tube heat exchange \[1\]. PCHE has significant advantages such as high pressure resistance, corrosion resistance, large temperature zone span, long design life and economy \[2-3\]. It is an advanced heat exchanger with great potential for future application in the ship nuclear power platform S-CO\textsubscript{2} power generation system.

Figure 1. Ship nuclear power platform.
PCHE has been adopted in the recuperator and cooler of the SANDIA National Laboratory's 100-kilowatt S-CO₂ cycle test system. The recuperator power is 2.16 times that of the electric heater, which verifies the efficiency and compactness of PCHE [4]. The Korea Energy Research Institute has built two S-CO₂ cycle test platform are established with the power rating of kilowatts and 10 kilowatt class respectively. The PCHE with a power rating of 600 kW is adopted to heat exchanger and cooler [5]. At present, the British company Heatric has mastered the PCHE manufacturing process. PCHE has been used in natural gas liquefaction/gasification plants for refrigeration cryogenic, petrochemical, onshore and offshore fixed platforms [6]. The PCHE design process is mainly composed of flow heat transfer design process and structural design process. Most of the current research focuses on flow heat transfer design, including PCHE flow heat transfer correlation [7], PCHE micro channel geometry design [8], PCHE flow rate distribution characteristics [9] and so on. Relatively conservative empirical values are adopted to the structural geometric parameters for the external solid part and the adjacent heat exchange channels of the PCHE to ensure structural strength safety requirements. The effect of the load caused by the fluid flow and heat transfer on the structural strength safety is not considered. It is thus difficult to quantitatively evaluate the structural safety of the PCHE design scheme. X Q Zhang perform the PCHE structural finite element numerical analysis by the single-section 3D solid channel model [10]. The effects of different working fluid pressure loads on the structural stress and deformation of the channel are studied. However, it is difficult to consider the coupling effect of structural deformation between multi-layer channels in single-section solid model. It is also difficult to reflect the influence of the actual structural boundary conditions of PCHE on the structural deformation field and stress field.

In this paper, the PCHE thermal-structural coupling numerical model of S-CO₂ Brayton cycle power generation system is established. The deformation and stress distribution of PCHE structure under the combined action of thermal load and pressure load are studied. The work of this paper provides technical support for the further development of PCHE structural design optimization and experimental verification research in the future.

2. PCHE scheme design for S-CO₂ recuperator

2.1 Design input

The S-CO₂ simple regenerative Brayton cycle system is adopted as the research background. According to the results of system heat balance analysis, the thermal parameters on the system key nodes are extracted as PCHE design inputs for the recuperator.

| Number | Variable                          | Unit | Value      |
|--------|----------------------------------|------|------------|
| 1      | Hot side/Cold side working fluid | —    | S-CO₂      |
| 2      | Hot side inlet pressure          | MPa  | 7.96       |
| 3      | Hot side inlet temperature       | °C   | 440.08     |
| 4      | Hot side outlet temperature      | °C   | 95.32      |
| 5      | Cold side inlet pressure         | MPa  | 14.10      |
| 6      | Cold side inlet temperature      | °C   | 75.35      |
| 7      | Cold side outlet temperature     | °C   | 359.34     |
| 8      | Hot side/Cold side flow rate     | kg/s | 0.015      |
| 9      | Channel type                     | —    | Semicircular straight channel |

2.2 Design result of the PCHE

According to the PCHE design input parameters, the temperature difference between the inlet and outlet of the S-CO₂ recuperator is large and the physical properties of the recuperator vary greatly.
However, the rationality of the heat transfer performance estimation using the traditional logarithmic mean temperature difference method is open to question. Therefore, the self-developed PCHE design program based on distributed calculation method is adopted in the PCHE design process in this paper. The PCHE design program performs heat transfer and resistance calculation based on the Gnielinski correlation. And the PCHE is calculated step by step by length. The physical properties of the hot side and cold side in each step range are updated according to the inlet temperature and pressure by the NIST REFPROP software. The temperature difference is calculated by the inlet hot side and cold side temperature in each step. Moreover, the local heat transfer coefficient, heat exchanging quantity, and pressure drop in each step are calculated. The temperature and pressure of the outlet in the step range are obtained as the inlet conditions for the next step calculation. Finally, the calculation is terminated when the heat exchanging quantity reaches the rated heat exchanging quantity. Compared with the traditional logarithmic mean temperature difference method, the distribution calculation method uses the temperature distribution along the path instead of the inlet and outlet conditions to calculate the temperature difference adopted in the heat exchange process is more reasonable.

### Table 2. Design results of the PCHE.

| Number | Variable                                           | Unit   | Value |
|--------|----------------------------------------------------|--------|-------|
| 1      | Channel diameter                                   | mm     | 1.4   |
| 2      | Heat exchange zone length                          | mm     | 713   |
| 3      | Lateral spacing of adjacent holes                  | mm     | 1     |
| 4      | Longitudinal spacing of adjacent holes             | mm     | 1     |
| 5      | Number of hot side and cold side plates           | layer  | 10    |
| 6      | External solid part thickness of the PCHE          | mm     | 20    |
| 7      | Number of horizontal micro channels                | —      | 8     |
The S-CO\textsubscript{2} recuperator design result is obtained using the self-developed PCHE design program. Figure 4 shows the PCHE three-dimensional model and the fine channel section of the recuperator. Figure 5 and Figure 6 show the S-CO\textsubscript{2} temperature and heat transfer coefficient distribution along the PCHE channel. It can be seen that the heat transfer coefficient in the longitudinal direction of the hot side channel fluctuates slightly around 2000 W/(m\textsuperscript{2}\cdot K). In contrast, the heat transfer coefficient of the cold side channel fluctuates greatly along the length direction. The heat transfer coefficient decreases from 3500 W/(m\textsuperscript{2}\cdot K) at the inlet to 2200 W/(m\textsuperscript{2}\cdot K) at the outlet. Since the physical property state at the inlet of the cold side channel is close to the critical point region, the drastically changing physical properties have a great influence on the heat transfer coefficient. Moreover, the total pressure drop on the hot side channel is 0.014 MPa, and the total pressure drop on the cold side channel is 0.008 MPa.

![Figure 5. Temperature distribution of S-CO\textsubscript{2} working fluid in PCHE channel.](image)

![Figure 6. Heat transfer coefficient distribution of S-CO\textsubscript{2} working fluid in PCHE channel](image)

3. Thermal stress analysis of PCHE

3.1 Thermal-structural coupling analysis process of PCHE

Under the temperature load of S-CO\textsubscript{2} working fluid, the thermal expansion degree for each local structural region of PCHE is inconsistent. This results in the generation of thermal stress in the PCHE structure. Therefore, the thermal stress problem of the PCHE structure is derived from the interaction between two physical fields of heat and stress, which is a typical coupled field analysis problem. Based on the large-scale finite element analysis software ANSYS, combined with the parameterized programming language APDL, the sequential coupling method is applied to conduct the thermal-structural coupling analysis of PCHE. The analysis process of is shown in Figure 7.

![Figure 7. PCHE thermal-structural coupling numerical analysis process](image)

3.2 3-D computational geometry model and meshing

The structure is simplified according to the design result of PCHE. The core structure and support structure are extracted to construct the 3-D calculation model of PCHE thermal analysis.
In this paper, the core heat exchange channel region is divided by relatively dense three-dimensional hexahedral solid elements. Other region is divided by relatively sparse three-dimensional hexahedral solid elements. The interfaces between the two regions use the coupling connection to transmit the degree of freedom information, which not only ensures the calculation accuracy but also the calculation efficiency. The total number of nodes of the calculation model is 1.68 million, and the total number of elements is 1.55 million.

3.3 Thermal analysis

The PCHE material performance parameters are shown in Table 3. The material type of PCHE is austenitic stainless steel 06Cr17Ni12Mo2 (S31608).

| Number | Variable               | Unit         | Value       |
|--------|------------------------|--------------|-------------|
| 1      | Material type          | —            | 06Cr17Ni12Mo2 (S31608) |
| 2      | Density                | kg/m³        | 8000        |
| 3      | Elastic Modulus        | GPa          | 169         |
| 4      | Poisson's ratio        | —            | 0.3         |
| 5      | Linear expansion coeff. | °C⁻¹        | 18.5×10⁻⁶   |
| 6      | Thermal Conductivity   | W/(m•°C)     | 21.5        |
| 7      | Yield Strength         | MPa          | 121         |

According to the distribution result of S-CO₂ temperature and heat transfer coefficient in micro channel obtained by PCHE design scheme, corresponding boundary conditions are applied to the calculation model.
1) Based on the heat transfer coefficient and the temperature distribution curve shown in figure 5 and figure 6, the heat transfer coefficient value and the temperature value at the local region of the micro channel are calculated by the linear difference method. This process is automatically conducted by APDL programming. Therefore, the convection boundary condition in the PCHE channel is applied.

2) The actual PCHE will be laid on the outside of the insulation layer. As a result, the adiabatic boundary condition is applied to the outer surface of the PCHE calculation model. That is, the heat flux density value is zero.

The temperature field distribution of the PCHE structure is obtained by steady state thermal analysis. Figure 12 shows that the PCHE structure temperature value gradually decreases along the X direction. The temperature distribution on the cross section of the same X coordinate is relatively uniform. The temperature field of the structure is basically consistent with the temperature distribution of the S-CO$_2$ working fluid in the micro channel. The maximum temperature and minimum temperature values of the PCHE structure are located on the inlet and outlet end faces of the hot channel respectively. The values are 389 °C and 83 °C respectively.

3.4 Structural stress analysis

The temperature field distribution of the PCHE structure is obtained by thermal analysis above. On this basis, the structural stress analysis is carried out. The following boundary conditions are specifically applied.

1) First of all, the thermal analysis element is converted into the structural analysis element. The temperature field calculation result obtained by thermal analysis is read and loaded into the PCHE calculation model as a body load.

2) Secondly, degrees of freedom constraints in the XYZ and YZ directions are applied to the bottom nodes of the two support structures.

3) Finally, the pressure loads at the corresponding inlets are applied to the nodes of the cold and hot channel internal surfaces respectively. The values are 14.10 MPa and 7.96 MPa respectively.
The thermal deformation and thermal stress results of the PCHE structure under the combined action of temperature load and pressure load are obtained by structural static analysis. It can be seen from figure 13 that the maximum total displacement value of the PCHE structure is 2 mm, which is located at the inlet surface of the hot channel. It can be seen from figure 14 that the maximum equivalent stress of PCHE is 117 MPa, which is also located at the sharp corner of the first layer on the inlet surface of the hot side. As a result, the maximum equivalent stress of the PCHE structure is less than the material yield limit and meets the strength safety requirements. It can be observed that the equivalent stress value of the vast area in the PCHE structure is less than 78.2 MPa. This value is much smaller than the material yield limit. The margin of the structural size value of the current PCHE solid area is relatively large. Therefore, the structure size parameters can be further optimized to effectively improve the PCHE compactness.

![Von-Misses stress distribution of the hot side inlet cross section (Pa).](image1)

![Von-Misses stress distribution of the cool side inlet cross section (Pa).](image2)

It can be seen from figure 15 and figure 16 that the stress distribution of the heat exchange channel near the central region in the cross section of the PCHE has a certain degree of similarity and periodicity. Under the influence of structural boundary conditions, the stress distribution of the heat exchange channel near the outer region is significantly different from the stress distribution of the heat exchange channel near the central region. However, the maximum stress value of the PCHE structure often appears at the location of the heat exchange channel near the outer region. The three-dimensional global structure model used in this paper can avoid the calculation error caused by the local structural model containing only partial periodic heat transfer channels. Therefore, a complete and reliable PCHE thermal stress calculation result is obtained.

4. Conclusions

In this paper, the S-CO\textsubscript{2} recuperator design scheme is obtained by the self-developed PCHE design program. Based on the ANSYS software combined with the parametric programming language APDL, the sequential coupling method is applied to perform the thermal-structural coupling numerical analysis of PCHE. The main conclusions are as follows:

1) The maximum total displacement and the maximum equivalent stress of the PCHE structure are 2 mm and 117 MPa respectively. The positions are both located at the inlet surface of the hot side channel. The maximum equivalent stress of the PCHE structure is less than the material yield limit and meets the strength safety requirement.

2) The equivalent stress of most regions in PCHE is much smaller than the yield limit of the material. The current PCHE structure design has a large margin. Therefore, the PCHE compactness can be further improved by the optimized design of size parameters.

3) The three-dimensional global structure model used in this paper can avoid the calculation error caused by the local structural model containing only partial periodic heat transfer channels. As a result, a complete and reliable PCHE thermal stress calculation result is obtained.
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