Numerical Simulation and Analysis for the Decay Heat Exchanger of China Prototype Fast Reactor

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Abstract. Decay heat exchanger (DHX) is an essential piece of equipment of the decay heat removal system (DHRS) in a pool-type sodium-cooled fast reactor. The main function of DHX is to transfer heat from primary circuit fluid (liquid sodium) to secondary circuit fluid (liquid sodium) of DHRS, which can reduce the high temperature caused by decay heat in the reactor core. In this paper, CFD method was used to simulate the statistic three-dimensional flow field of DHX which is used in China Prototype Fast Reactor under several different operating conditions. The numerical results under rated operating conditions were compared with the design values and the comparison was fit in with expectation, which demonstrated the validity of the numerical model. The study of the flow field of DHX under designed operating conditions was conducted to obtain the heat transfer features and the flow characteristics. The results show that the design of DHX in China Prototype Fast Reactor is sufficient to the purpose to timely bring the decay heat out of the reactor core and DHX meets the safety design requirements from the perspective of heat transfer. The work in this paper provided references for further design improvement of the DHX in a pool-type sodium-cooled fast reactor.

1. Introduction
China Prototype Fast Reactor is a kind of pool-type sodium cooled fast reactor, reactor core and most pieces of the essential equipment are immersed in the liquid sodium pool. The decay heat removal system (DHRS) which consists of 4 independent loops is an important safety system. There are one DHX and one Sodium-Air Heat Exchanger in each loop. The whole system is driven by natural circulation and delivers the heat to the air finally through the Sodium-Air Heat Exchanger. The primary fluid flow driving force of DHX is the temperature difference and the potential difference between the reactor core and the DHX, while the secondary fluid flow driving force of DHX is the temperature difference and the potential difference between the Sodium-Air Heat Exchanger and the DHX.

Up to now, several scholars have done research about the decay heat removal system and have applied for the patent of the fully passive decay heat removal system which utilizes one kind of decay heat exchanger [1, 2].

Research about the DHX of China Experimental Fast Reactor (CEFR) have been done by Chinese scholars [3, 4]. However, the installed capacity of China Prototype Fast Reactor is much higher than that of CEFR, which means that DHX designed thermal power of China Prototype Fast Reactor is larger than that of CEFR. The design of DHX has already been conducted to obtain the structure parameters which meet the demand of the higher thermal power from DHRS and other design requests.
The DHX designed for China Prototype Fast Reactor has been simulated by using CFD method with ANSYS CFX. The temperature and thermal power have been calculated to make sure that the design of DHX is reasonable. Heat transfer and flow characteristics have been analyzed according to the results of numerical simulation to further understand how DHX functions and what the disadvantages are for heat transfer, which can help to improve the design of DHX in the future.

2. Design parameters and geometric model
Decay heat exchanger (DHX) consist of Central pipe Shell, Outlet pipe, Discharge chamber, Inlet window, Outlet window, Tube bundle and Bottom chamber. Inner and outer Shell form the flow pass for the primary fluid, while Central pipe, Bottom chamber and tube bundle form the pass for the secondary fluid.

The heat exchanging area is the area between the upper tube plate and the bottom tube plate.

When reactor accident happens, the temperature of the sodium pool is 535°C, which is the inlet temperature of DHX. The designed thermal power of one single DHX is 9MW. The outlet temperature is requested to be 450°C. Other design parameters are listed in Table 1.

![Figure 1. The schematic of DHX](image)

| No. | Name of component   | Parameters                  | Units | Values |
|-----|---------------------|-----------------------------|-------|--------|
| 1   | Central pipe        | Designed thermal power      | MW    | 9      |
| 2   | Shell               | Primary inlet temperature   | °C    | 535    |
| 3   | Outlet pipe         | Primary outlet temperature  | °C    | 450    |
| 4   | Discharge chamber   | Secondary inlet temperature| °C    | 380    |
| 5   | Tube bundle         | Secondary outlet temperature| °C    | 520    |
| 6   | Bottom chamber      | Primary mass flow           | kg/s  | 84     |
| 7   |                     | Secondary mass flow         | kg/s  | 50     |
| 8   |                     | Designed temperature        | °C    | 580    |
| 9   |                     | Secondary designed pressure | MPa   | 1.0    |
| 10  |                     | Secondary operating pressure| MPa   | 0.8    |
Physics properties of liquid sodium for calculation is obtained from reference [5]. The calculating formulas are as follows:

\[
\rho = 16.0185 \times [59.566 - 7.9504 \times 10^{-4}(1.8t + 32) \\
-0.2872 \times 10^{-4} \times (1.8t + 32)^2 + 0.0603 \times (1.8t + 32)^3]
\]  

(1)

\[
\frac{C_p}{T} - 4.1868 \times [0.389352 - 1.10599 \times 10^{-4}(1.8t) \\
+3.41178 \times 10^{-8} \times (1.8t)^2]
\]  

(2)

\[
\lambda = 1.72958 \times [54.306 - 1.878 \times 10^{-2} \times (1.8t + 32) \\
+2.0914 \times 10^{-6} \times (1.8t + 32)^2]
\]  

(3)

\[
\eta = 4.134 \times 10^{-4} \exp\{2.302585 \times [1.0203 \\
+397.17 / (1.8t) - 0.4925 \times \lg(1.8t)]\}
\]  

(4)

\(\rho\) is the density of the liquid sodium (kg/m3), \(C_p\) is the constant-pressure specific heat (J/(kg·K)), \(\lambda\) is the thermal conductivity (W/(m·K)), and \(\eta\) is the viscosity (Pa·s). These properties are all functions of temperature \(T\) (K) or \(t\) (℃).

The structure of the outlet window and the inlet window are similar which is a annular plate with orifices showed in Fig 2. There are 15 rows of orifices with a diameter of 50mm and each row contents 24 orifices.

![Figure 2. Structure of the inlet window](image-url)

Figure 2. Structure of the inlet window

Figure 3 shows the structure of the tube bundle. Heat transfer tube bundle is formed by 285 and is divided into 5 layers. There are 69 tubes evenly distributed in the innermost layer. The number of each layer increases by 6. Figure 4 shows that the tubes are periodically distributed in a period of 120°. To reduce the computational complexity, 1/3 of the total model is selected for calculation, such as Fig 3 shows.

![Figure 3. Tube bundle geometric model](image-url)

Figure 3. Tube bundle geometric model

![Figure 4. Tube bundle geometric model](image-url)

Figure 4. Tube bundle geometric model

The calculation model consist of the tube bundle area, primary fluid flow field and the secondary fluid field.
3. Mathematic Models

3.1. Basic Assumptions
According to the physic model of the DHX described above, several assumptions have been made as follow:

1) The heat transfer system is at a steady state and adiabatic;
2) Because the fluid flow driving force of DHX is the temperature difference and the potential difference, it is hard to set the boundary conditions and to give an exact inlet flow direction. In order to make the flow condition be as close as possible to the real situation, an annular region was added surrounding the inlet and outlet window and the mass flow of the outer wall of the annular region was set as a constant to make sure that the fluid flows from a far place and flows into the inlet window with a low velocity. In a similar way, there is also another annular region surrounding the outlet window to make sure that the fluid flow to different directions after it comes out of the outlet window.
3) In early analyzing stage, the study focus on the characteristics of the entire flow field. It has been proved that using straight tubes instead of regional spiral tubes have little effect on the heat transfer features near inlet/outlet area and most of the straight tubes area. Thus it is assumed that the tubes in the DHX are all straight tubes.

3.2. Basic Governing Equations
The flow and heat transfer of fluid can be described by the mass conservation law, the momentum conservation law and the energy conservation law. The governing equations are the mathematical descriptions whose universal form of Euler method is as follows:

$$\frac{\partial \rho \phi}{\partial t} + \text{div}(\rho U \phi) = \text{div}(\Gamma_v \text{grad} \phi) + S_\phi$$

(5)

$\phi$ is an universal variable which can represent variables such as mass-flow rate, velocity, temperature and enthalpy of one particular fluid control volume. $\rho$ is the density and $U$ is the velocity of the fluid in the control volume. $\Gamma_v$ is the Generalized diffusion coefficient. $S_\phi$ is the source term.

4. Boundary Conditions and Mesh
Table 2 shows the boundary settings for numerical simulation. Primary and secondary inlets are all set as mass-flow-inlet.
Figure 6. (a) Mesh of the calculation area  
(b) Mesh of primary inlet area

Figure 6. The mesh of DHX for numerical simulation

Table 2. Boundary settings for numerical simulation

| Boundary name      | Boundary type     | Values         |
|--------------------|-------------------|----------------|
| Primary inlet      | mass-flow-inlet   | 28kg/s         |
| Secondary inlet    | mass-flow-inlet   | 16.67kg/s      |
| Primary outlet     | opening           | -              |
| Secondary outlet   | outlet            | -              |

Figure 6 shows the mesh of DHX for numerical simulation. The grid quantity is about 30 million.

5. Organization of the Text Results and Analysis

5.1. The Outlet Temperature of The Primary and Secondary Fluid

Primary/Secondary outlet thermal parameters (calculated values) are listed in Table 3. It can be found that the outlet temperature of the primary and secondary fluid have a tiny deviation from the design value.

Table 3. Primary/Secondary outlet thermal parameters

| Section                        | Design value | Calculated value | Deviation from design value |
|--------------------------------|--------------|------------------|----------------------------|
| Primary outlet cross section   | 723.15K/450℃ | 719.46K/446.31℃ | -0.01%                     |
| mean temperature               |              |                  |                            |
| Secondary outlet cross section | 793.15K/520℃ | 803.73K/530.58℃ | 2.03%                      |
| mean temperature               |              |                  |                            |

The deviation may be caused by the simplification of the calculation model (such as the assumption that the tubes are all straight). The deviation between primary and secondary thermal power is 2.56%, which is acceptable and meets the calculation requirements.
5.2. Temperature Distribution Features of The Primary/Secondary Flow Field

The temperature distribution of the tube bundle outlet plane is shown in Fig 7. It can be found that the temperature of the innermost layer is the lowest and the temperature in tubes increases from inside to outside, the highest temperature is at the outermost layer.

![Figure 7. Tube bundles outlet plane temperature field (secondary flow field)](image)

The heat transfer performance of a shell-and-tube exchanger depends on the coupling effect between fluid in the tube pass and the shell pass. In the regions near the inlet window, the primary fluid scours the tube bundle with cross flow which is perpendicular to the axis of the tube bundle. Along the primary fluid flow direction, the flow is gradually changing into axial flow until the fluid comes to the outlet window and flows cross the tube bundle.

To study further about how the flow characteristics influent the heat transfer, the temperature at the axial section has been extracted as showed in Fig 8.

![Figure 8. Temperature distribution at the axial section](image)

It can be found in Fig 8 that the temperature distribution of both the primary fluid and the secondary fluid is relatively even in the region near the inlet windows, while in the region near the outlet window the temperature distribution is relatively large.
To get a more precise regulation of the distribution along the tube, the temperature data is extracted from five central lines in five different tubes from each tube layer.

It can be found in Fig 10 that, the secondary fluid is heated by the primary fluid along the secondary flow direction (-Y direction). The maximum temperature difference happens in the region near the primary outlet window with a difference of 32K.
Figure 12. Temperature distribution along the five lines outside the tubes (primary fluid flow region)

The temperature data near the outer wall of the tubes is extracted from five lines outside five different tubes from each tube layer, as showed in Fig 11.

It is shown in Fig 12 that the primary fluid is cooled by the secondary fluid along the primary flow direction (+Y direction). The maximum temperature difference happens in the region near the primary outlet window with a difference of 90K.

6. Conclusions

The numerical simulation of the DHX designed for China Prototype Fast Reactor has been conducted to obtain the heat transfer and the flow characteristics in this paper. The conclusions are as follows:

The primary outlet average temperature of DHX is 446.31℃ while the secondary outlet average temperature is 530.58℃. The deviations between primary and secondary thermal power 2.56% which is acceptable and meet the calculation requirements.

According to the analysis about the temperature distribution inside and outside of the heat transfer tubes in different layer, the maximum temperature difference happens in the region near the outlet window both for the primary fluid and the secondary fluid. The maximum temperature difference in primary fluid is about 90K, while that in the secondary fluid is about 32K.

The uneven distribution in both primary and secondary fluid has negative effect on the heat transfer efficiency and may cause thermal stress on the device. Thus the future work is to focus on the improvement of the flow field to lower the unevenness of the temperature distribution based on the study in this paper in order to improve the design of the DHX.

References

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