Optimization design method of PRHRS air heat exchanger based on natural circulation characteristics

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Abstract: Passive residual heat removal system (PRHRS) was the key equipment to ensure the inherent safety of the fourth generation of nuclear reactors, which can effectively reduce the probability of core meltdown in the event of an accident. A multi-physics coupling model of sodium cooled fast reactor PRHRS was established in this paper, which based on the natural circulation characteristics of PRHRS. The model was analytically calculated according to the flow balance and energy balance, and finally the model was dynamically balanced. The influence of the tube spacing of the serpentine finned tube and the opening area of the air door on the thermal behavior of the system was analyzed through PRHRS model, and the optimal design method of the air heat exchanger (AHX) of PRHRS was mastered. The research results provide a theoretical basis for the rational design of the air heat exchanger and the safe operation of the sodium cooled fast reactor PRHRS.

1. Introduction
The safety and reliability of nuclear power systems have been received more and more attention after the nuclear accident in Fukushima, Japan [1-3]. At present, the cooling methods of the passive residual removal system (PRHRS) mainly include water cooling and air cooling. Compared with the water cooling method, the method of using air as a cooling medium is not restricted by geographical location, and is convenient for nuclear power facilities in water shortage areas.

Because of these advantages, research on air-cooled PRHRS air heat exchanger has gradually deepened in recent years. Hie-Chan Kang et al. [4-5] found that the pressure drop and heat transfer coefficient of the air heat exchanger did not change much when tube banks were arranged in the rectangular pattern and the parallelogram pattern according to the study of Korea advanced liquid Metal reactor PRHRS. However, the pressure drop and heat transfer coefficient of the staggered tube banks were higher than the parallelogram tube banks by 80% and 40% respectively. V. Vinod et al. [6-7] conducted a forced ventilation test on the sodium-air heat exchanger in the Indian prototype fast breeder reactor (PFBR). The results showed that the heat transfer coefficient of the sodium-air heat exchanger is mainly determined by the air side heat resistance. Li Jing et al. [8] used CFD software to calculate the natural circulation flow in the air heat exchanger of China experimental fast reactor, and gave the air velocity distribution and temperature distribution in the air heat exchanger under various working conditions. Finally, the change law of the heat removal capacity of the air heat exchanger with the outdoor temperature and the sodium tube temperature was summarized.

In summary, the experimental and numerical methods for PRHRS air heat exchangers of the third generation and the fourth generation reactor are mostly used, and there are few analytical models to be studied, especially the analytical modeling for the fourth generation reactor. Therefore, a multi-physics
coupling model of sodium cooled fast reactor PRHRS is established in this paper, which is based on the characteristics of natural circulation. The general thermal equation of the sodium cooled fast reactor PRHRS is obtained by formula derivation, and the calculation software is used to analyze and calculate the system flow and obtain the relevant thermal parameters. Finally, the influence of the variation of the tube spacing of serpentine fin tube and the opening area of air door on the heat transfer and flow of the PRHRS air heat exchanger is explored, and the optimal design method of the PRHRS air heat exchanger is mastered.

2. Heat transfer and flow model of PRHRS

Figure 1 is a schematic diagram of the model of the sodium cooled fast reactor PRHRS. In the model, temperature field, density field and pressure field interact with each other and reach dynamic equilibrium. The system mainly consists of the air heat exchanger (AHX), the decay heat exchanger (DHX), and the chimney and the air door. The system includes of three natural circulation sections, the DHX in the hot sodium pool and reactor core constitute a natural circulation of the first loop, then the DHX and the AHX constitute the natural circulation of the intermediate loop, and finally the AHX in the chimney and the external environment constitute a natural circulation of air cooling.

The total heat transfer amount of the PRHRS air heat exchanger is calculated as

$$Q_o = \phi K n_s N_p L_o A_o \Delta T_m$$

(1)

Where

$$K = \left[ \frac{\beta}{h_s} + r_s \beta + \frac{A_o}{2 \pi \lambda_w} \ln \left( \frac{d_i}{d_o} \right) + \frac{r_s}{\eta} + \frac{1}{h_s \eta} \right]^{-1}$$

(2)

In formula (1), $K$ is the total heat transfer coefficient of the AHX, $W/m^2.K$; $n_s$ is the number of tube; $N_p$ is the number of tube passes; $L_o$ is the length of the tube per pass; $A_o$ is the outer surface area of the fin tube base tube per unit length, $m^2/m$; $\phi$ is the logarithmic mean temperature difference correction coefficient; $\Delta T_m$ is the logarithmic mean temperature difference, °C.

In formula (2), $h_s$ and $h_o$ are the sodium side and air side heat transfer coefficients, respectively, $W/m^2.K$; $r_s$ and $r_o$ are the sodium side and air side fouling thermal resistance, $m^2.K/W$; $d_i$ and $d_o$ are inner and outer diameters of finned tube base tube, respectively, $m$; $\beta$ is the finned ratio; $\eta$ is the total efficiency of the finned tube wall surface; $\lambda_w$ is the thermal conductivity of the tube material, $W/m.K$. 
In the chimney channel, the buoyancy force of the height of H1 chimney on the air is given as follow

\[ F_a = \int_{0}^{H1} (\rho_a - \rho_{a,om}) gdh \]  

In formula (3), \( \rho_a \) is the air density at ambient temperature, \( \text{kg/m}^3 \); \( \rho_{a,om} \) is the air density at average value between the outlet temperature of the AHX and the outlet temperature of the chimney, \( \text{kg/m}^3 \).

The total pressure drop on the air side is given

\[ \Delta P_a = f_sN_pN_x \left( \frac{G_{max}}{2\rho_{a,m}} \right)^2 + f_x \left( \frac{m_a/S_a}{2\rho_{a,m}} \right) H_1 + \xi_xN_x \left( \frac{m_a/S_x}{2\rho_{a,m}} \right)^2 + \varepsilon_c \left( \frac{m_a/S_c}{2\rho_{a,m}} \right)^2 \]  

In formula (4), \( G_{max} \) is the maximum mass flow rate among the bundles, \( \text{kg/m}^2\cdot\text{s} \); \( m_a \) is the air mass flow rate, \( \text{kg/s} \); \( S_a \) is the cross-sectional area of the chimney channel, \( \text{m}^2 \); \( H_1 \) is the height of the chimney, \( \text{m} \); \( f_s \) is the frictional resistance coefficient among the bundles; \( f_x \), \( \xi_x \) and \( \varepsilon_c \) are the friction coefficient of the chimney, the local resistance coefficient and the resistance coefficient of the inlet and outlet, respectively.

The heat loss of the pipeline can be neglected because the heat loss of the pipeline and the environment is small, so the buoyancy force of sodium side is given as follow

\[ F_s = \int_{0}^{H1} (\rho_{s,n} - \rho_{s,i}) gdh \]  

In formula (5), \( \rho_{s,i} \) is the sodium density of the DHX outlet, \( \text{kg/m}^3 \); \( \rho_{s,n} \) is the sodium density of the AHX outlet, \( \text{kg/m}^3 \); \( H_2 \) is thermal center height difference between the AHX and the DHX, \( \text{m} \).

The resistance loss inside the pipe is given as follow

\[ \Delta P_s = \sum_{i=1}^{N_{i}} f_{s,i} \left( \frac{\rho_{a,m}y_{s,i}^2}{2} \right) + \xi_{s,i}N_{i} \left( \frac{\rho_{s,n}y_{s,i}^2}{2} \right) \]  

In formula (6), \( f_{s,i} \) is the friction resistance coefficient inside the pipe, \( L_{s,i} \) is the length of each pipe, \( \text{m} \); \( N_{i} \) is the number of pipe bends; \( \xi_{s,i} \) is the local resistance coefficient in the pipe.

Combined with formula (3) and formula (4), it can be found that there are many factors affecting the ventilation mass flow rate of PRHRS air heat exchanger, which is related to the ambient temperature, chimney geometry, finned tube geometry and heat loss.

3. Flow chart of PRHRS

Figure 2 is the cyclic flow chart of the sodium cooled fast reactor PRHRS. The flow is mainly divided into four calculation procedures, including two flow balance calculation modules and one energy balance calculation module, and each module must be performed a balance determination.

(1) The air side buoyancy force \( F_a \) is calculated according to the equation (3), and the air side total pressure drop \( \Delta P_a \) is calculated according to the equation (4). Judging the relative error between the two, the air side flow balance is determined if the relative error is within 1\%, and the system energy balance calculation is entered. Otherwise, the air side outlet temperature is adjusted.

(2) The sodium side buoyancy force \( F_s \) is calculated according to the equation (5), and total resistance loss \( \Delta P_s \) is calculated according to the equation (6). Judging the relative error between the two, the sodium side flow balance is determined if the relative error is within 1\%, and the system energy balance calculation is entered. Otherwise, the sodium side inlet and outlet temperature is adjusted.

(3) The total heat transfer amount \( Q_o \) is calculated by the formula (1), and the relative error between the \( Q_o \) and the designed heat load \( Q \) is judged. The system energy balance is determined and the thermal parameters are outputed if the relative error between both is within 1\%. Otherwise, the inlet and outlet temperatures on both sides of the flow balance module are adjusted.
(4) After the system flow balance and energy balance are determined, the physical characteristic parameters of the fin tube and the structural parameters of the related equipment are adjusted, which is to obtain the optimized design result of AHX.

![Flow chart of the sodium cooled fast reactor PRHRS.](image)

Figure 2. Flow chart of the sodium cooled fast reactor PRHRS.

### 4. Calculation results and analysis

**Table 1. Design heat load and main structural parameters of PRHRS.**

| Design Parameters          | Design Parameters          |
|----------------------------|----------------------------|
| Design heat load [MW]      | 2                          |
| ID of tube [mm]            | 32.9                       |
| OD of tube [mm]            | 38.1                       |
| Transverse tube spacing [mm]| 85                         |
| Fin height [mm]            | 13                         |
| Fin thickness [mm]         | 1.22                       |
| Fin pitch [mm]             | 5.1059                     |
| Number of tubes per row    | 22                         |
| Tube arrangement [°]       | 30                         |
| Ambient temperature [°C]   | 40                         |
| Chimney height [m]         | 1                          |
| Chimney inner diameter [m] | 1                          |
| Thermal center height [m]  | 41.5                       |
| Tube material              | 316L                       |

According to the experimental model from literatures [6-7]. Table 1 lists the design heat load of the sodium cooled reactor PRHRS, the main structural parameters of the finned tube and the related equipment.

As shown in Figure 3a, with the increase of tube spacing, the air side outlet temperature of the AHX decreases, while the sodium inlet and outlet temperature increase. This is because the increase of tubes spacing leads to a reduction in the total heat exchange area of the fin tubes while increases the inlet air flow. As shown in Figure 3b, the total heat transfer coefficient and pressure drop of the AHX
decrease with the increase of tube spacing, and the decreasing trend is slowing down. This is because although the cross-sectional area between tube bundles increases with the increase of tube spacing, the inlet air flow rate increases correspondingly, so the speed rate of the air flow becomes slower. When the tube spacing increases from 70mm to 90mm, the total heat transfer coefficient reduces by 13.64%, the heat exchanger pressure drop reduces by 90.75%, so the influence of the tube spacing on the pressure drop is greater. Therefore, the reduction of the pipe spacing increases the heat transfer coefficient and reduces the size of the tube bundle, while the increase of the pressure drop requires a higher height of the chimney, so the tube bundle size and the height of the chimney should be comprehensively considered in practical engineering designs.

Figure 3. The AHX thermal parameters under different tube spacing.

Figure 4. The AHX thermal parameters under different opening area of air door.

Figure 4a and Figure 4b show the thermal parameters of AHX as a function of the ambient temperature of -20 °C. It can be seen that when the opening area reduces to about 30%, the outlet temperature of sodium can increase by about 20 °C. At the same time, the opening area of air door reduces from 60% to 30%, the total heat transfer coefficient increases by 25.45%, and the total pressure drop (the sum of the AHX and the chimney) increases by 24.46%. Therefore, the method of reducing the opening area can effectively increase the operating temperature of the equipment and the heat transfer effect of the system when the PRHRS encounters extremely low temperature environmental conditions.
5. Conclusions
The multi-physics coupling model of the sodium cooled reactor PRHRS was established, and the calculation method of the system circulation process was given. The influence of the variation of the tube spacing of fin tube and the opening area of air door on the thermal behavior of the PRHRS was obtained. The following conclusions were reached in this study.

1. With the increase of the tube spacing, the inlet and outlet temperatures of the sodium side were increased, the total heat transfer coefficient and pressure drop of AHX were decreased and the trend was slowing down. The influence of the tube spacing on the pressure drop is much greater than the heat transfer coefficient. Therefore, the tube bundle size and the height of the chimney should be comprehensively considered in practical engineering designs.

2. When the PRHRS encountered extremely low temperature environmental conditions, the method of reducing the opening area of air door could effectively improve the operating temperature of the AHX and the heat transfer effect of the system.

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