

Thermal Hydraulic Analysis of RPV

Support Cooling System for HTGR

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Abstract: Passive safety is now of great interest for future generation reactors because of its reduction of human interaction and avoidance of failures of active components. reactor pressure vessel (RPV) support cooling system (SCS) for high temperature gas-cooled reactor (HTGR) is a passive safety system and is used to cool the concrete seats for the four RPV supports at its bottom. The SCS should have enough cooling capacity to ensure the temperature of the concrete seats for the supports not exceeding the limit temperature. The SCS system is composed of a natural circulation water loop and an air cooling tower. In the water loop, there is a heat exchanger embedded in the concrete seat, heat is transferred by thermal conduction and convection to the cooling water. Then the water is cooled by the air cooler mounted in the air cooling tower. The driving forces for water and air are offered by the density differences caused by the temperature differences. In this paper, the thermal hydraulic analysis for this system was presented. Methods for decoupling the natural circulation and heat transfer between the water loop and air flow were introduced. The operating parameters for different working conditions and environment temperatures were calculated.

Keywords: Thermal hydraulic analysis; HTGR; Support cooling system; Natural circulation; Passive safety

1. Introduction

Energy supply security is important matter for industrial and economical developments of a society. High temperature gas cooled nuclear reactor (HTGR) is a candidate of the primary energy source because of its inherent safety, economical efficiency and nuclear proliferation resistance. Passive safety system which does not rely on the electric power is widely used in HTGR^[1]. Since the design temperature and the operation temperature of the reactor pressure vessel are 350°C and 25°C respectively and the allowing temperature of concrete is 70°C in normal condition. Support cooling system (SCS) for High Temperature reactor is established for cooling the four bearing supports at the bottom of the reactor and ensure the temperature of the concrete near the supports not exceed the softening temperature. The support cooling system is designed to be a passive safety system, and the heat is removed by heat conduction and natural convection of the cooling water.

In this paper, the thermal hydraulic design method for SCS system was analyzed. The heat transfer of water and air were conducted in an air cooler, and the heat exchange quantity for water circulation and air circulation were calculated coupled.

The operating parameters for different working condition and environment temperature were calculated.

2. Support Cooling System (SCS)

Each reactor has its own SCS, and each SCS has two independent pipelines. One pipeline can satisfy the demand of heat removal, and the two pipelines complement each other. Under normal working condition, the objective quantity of heat removal is 23 kW per reactor. SCS is consisted by main pipelines for hot water and cold water, branch pipelines for hot water and cold water, expansion tank, air cooler and air cooling tower. The sketch map of SCS is shown is Fig. 1. The branch pipelines were connected to the four supports of the reactor. Cooling water in the branch pipelines was heated. Thus the water density decreases. The heated water flow upward to the main cold water pipe and finally reach the air cooler driven by the lift force caused by the density difference of the cold and hot water. The heated water was cooled by the air in air cooler, and then flow downward to the main cold pipeline and branch cold pipelines and finally flow back to the four supports at the bottom of the reactor. In the other hand, the air in air cooler was heated by the hot water and flow upward through the air cooling tower. The height of the air cooling tower is 6m in order to offer enough lifting force for air flow.

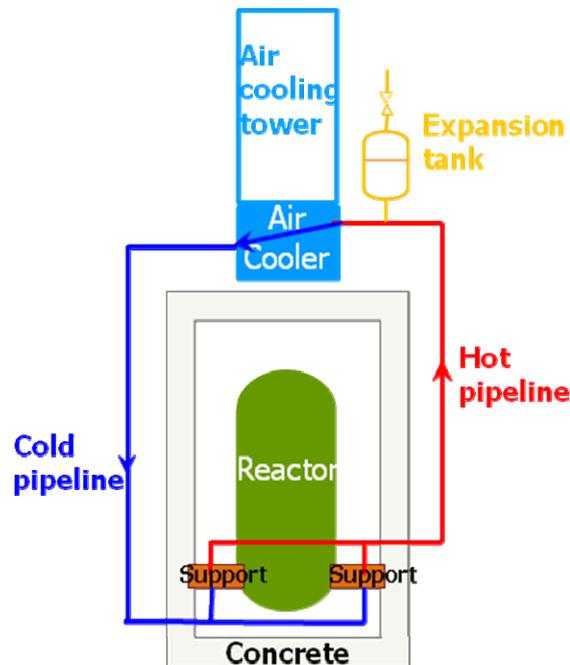


Fig.1 Sketch map of support cooling system.

3. Hydraulic analysis

3.1 Flow chart of calculation

The hydraulic calculation process is shown in Fig.2^[2]. Firstly, initial values would be supposed for the inlet and outlet air temperature. Then the mass flow rate and

Reynolds number could be calculated from the designed heat transfer quantity, thus the air flow resistance is got. The lifting force of air could be calculated from the inlet and outlet air temperature. So, if the air flow resistance is equal to the lifting force, the supposed value of inlet and outlet air temperature is correct, otherwise new value should be supposed. After the flow of air side is balanced. Initial values would be supposed for the inlet and outlet water temperature. Then the mass flow rate and Reynolds number of water flow could also be calculated from the designed heat transfer quantity, thus the water flow pressure drop is got. The lifting force of water could be calculated from the inlet and outlet water temperature. So, if the water flow pressure drop is equal to the lifting force, the supposed value of inlet and outlet water temperature is stage correct, otherwise new value should be supposed. After the flow of both air and water sides are balanced, the heat transfer quantity should be calculated. Firstly, the physical properties, Reynolds number and Prandtl number is calculated based on the qualitative temperature. Then Nusselt number is calculated for the air side and water side respectively. Thus the convective heat transfer coefficient could be got, and the overall heat transfer coefficient is determined. Finally the logarithmic mean temperature difference and total heat transfer quantity is calculated. If the calculated total heat transfer quantity is equal to the designed heat transfer quantity, the supposed value of inlet and outlet water temperature is correct, otherwise new value should be supposed until the heat transfer quantity of calculated and designed value is balanced. In general, two flow balance and one heat transfer balance should be considered in the hydraulic analysis of SCS.

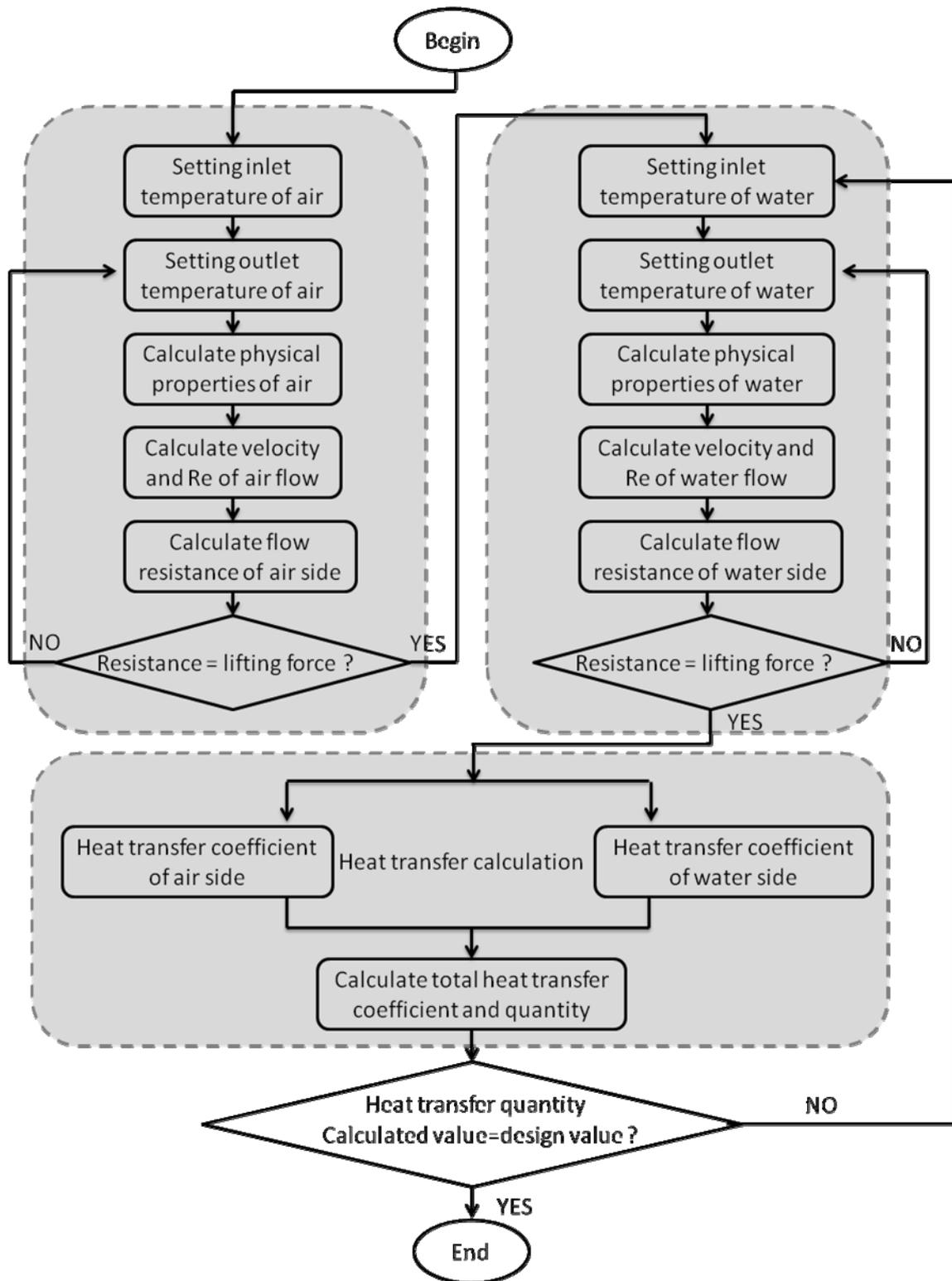


Fig.2 flow chart of hydraulic calculation of SCS system.

3.2 Calculation formula

The flow resistance of the pipeline and air cooler is consisted by friction resistance and local resistance, and is calculated by the following equation. ^[3-6]:

$$\Delta p = \sum_i \left(f_i 0.5 \rho u_i^2 \frac{L_i}{d_i} \right) + \sum_i \xi_i (0.5 \rho u_i^2) \quad (1)$$

where f_i is friction resistance coefficient, ξ_j is local resistance coefficient, u_i is the average flow velocity, L_i and d_i is the length and inner diameter of the pipe respectively.

The calculation formula of friction resistance coefficient is,

$$\begin{cases} \text{Re} < 2300, f \text{ Re} = 64 \\ \text{Re} > 2300, f = (1.82 \lg \text{Re} - 1.64)^{-2} \end{cases} \quad (2)$$

The calculation formula of flow resistance coefficient of tube bundle of air cooler is,

$$f = 37.86 \left(\frac{D_b G_{\max}}{\mu} \right)^{-0.316} \left(\frac{S_1}{D_b} \right)^{-0.927} \left(\frac{S_1}{S_2} \right)^{0.515} \quad (3)$$

where D_b is the outer diameter of the heat transfer tube, S_1 and S_2 are the transverse and longitudinal space between adjacent pipes, G_{\max} is the wind velocity flowing through the narrowest area, μ is the dynamic viscosity.

The lifting force of the air is,

$$\Delta p = (\rho_c - \rho_h) g H \quad (4)$$

Where ρ_c is the density of cold water, ρ_h is the density of hot water, g is the acceleration of gravity, H is the lifting height.

The Nusselt number of heat transfer tube of air cooler is calculated by different equations depending on the Reynolds number,

$$\begin{cases} \text{Re} < 2300, Nu_i = 1.86 (\text{Re Pr})^{1/3} \left(\frac{d}{L} \right)^{1/3} \\ \text{Re} > 2300, Nu_i = 0.116 (\text{Re}^{2/3} - 125) \text{Pr}^{1/3} \left(1 + \left(\frac{d}{L} \right)^{2/3} \right) \end{cases} \quad (5)$$

The Nusselt number of finned tube bundle is [5, 7]:

$$Nu_a = 0.1378 \left(\frac{D_b G_{\max}}{\mu} \right)^{0.718} \text{Pr}^{1/3} \left(\frac{Y}{H} \right)^{0.296} \quad (6)$$

Where Y and H are the fin spacing and fin height respectively.

The total quantity of heat transfer is,

$$Q = \Psi K A \Delta T_m \quad (7)$$

Where, $\Delta T_m = \frac{(T_i' - T_a'') - (T_i'' - T_a')}{\ln \left(\frac{T_i' - T_a''}{T_i'' - T_a'} \right)}$ is the logarithmic mean temperature difference,

Ψ is the coefficient of logarithmic mean temperature difference, K is the overall coefficient of heat transfer. T_i' and T_i'' are the inlet and outlet water temperature in

air cooler. T_a' and T_a'' are the inlet and outlet air temperature in air cooler.

The equation of K is,

$$K = \left(\frac{A}{h_i A_i} + \frac{1}{h_a} + R_f + R_i + R_o + R_w + R_g \right)^{-1} \quad (8)$$

where h_i is the convective heat transfer coefficient of inside heat transfer tube, h_a is the convective heat transfer coefficient of the fins, R_f is the fin heat resistance, R_i is the fouling resistance inside the tube, R_o is the fouling resistance of the fin, R_w is the thermal conduction resistance of pipe wall, R_g is the gap resistance. h_i is based on the the internal surface area, and other parameters are based on the external surface area. R_f , R_i , R_o and R_g are set to 16.3×10^{-4} , 3.4×10^{-4} , 1.7×10^{-4} and 0.7×10^{-4} respectively, the unit is $\text{m}^2\text{K}/\text{W}^{[7]}$.

Since the cross sectional area of air cooling tower is $3.2\text{m} \times 1.2\text{m}$, the length, L , and width, W , of air cooler is set to be 3m and 1m. Circular finned tube is used in the air cooler. the length of the tube is 3m. The arrangement of tube is shown in Fig.2. The parameters of air cooler and fins are list in Table.1.

The calculation results shows that the thermal resistance on the air side takes 70% of the total resistance, the flow resistance in tube takes 20% of the total resistance. The fin resistance, the fouling resistance and the gap resistance are

The calculation results of thermal resistance are list in Table.2.

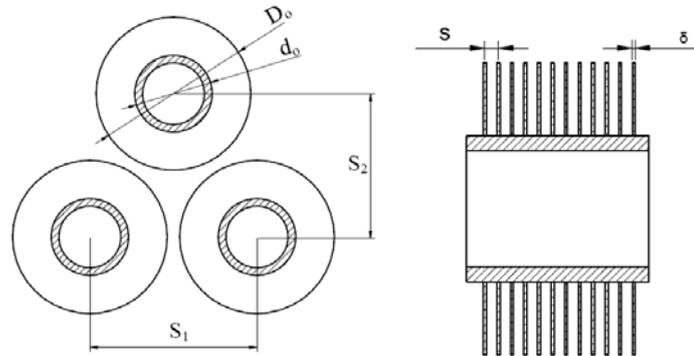


Fig.3 Sketch map of finned tube

Table1. Geometrical parameter of air cooler

d_i (mm)	d_e (mm)	S_1 (mm)	S_2 (mm)	L (mm)	D_0 (mm)	δ (mm)	s (mm)
20	25	54	46.8	2.7	50	0.5	2.3

The heat transfer efficiency of air cooler is influenced by the number of tube rows. There is a optimal number for tube rows. Fig.4 gives the calculation results of inlet and outlet temperature of air side and water side with different number of tube rows. It is obviously that, the outlet temperature of air side increases and outlet temperature of water side decreases as the number of tube rows increases. But when the number of tube rows is bigger than four, the outlet temperature of water side almost keeps constant. Thus the tube row number of the air cooler is set to four.

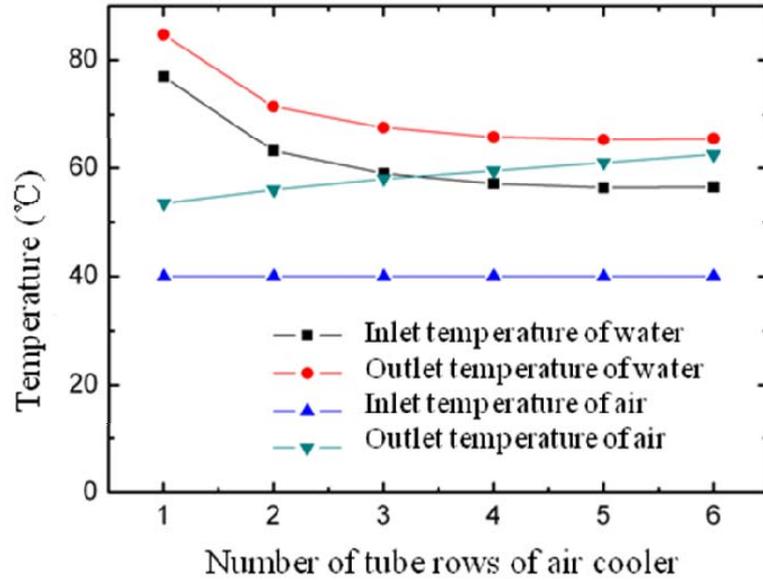


Fig. 4 influence of number of tube rows on inlet and outlet temperature of air cooler

4. Calculation results for different working conditions.

23kW heat should be discharged by cooling system. There are two systems in each reactor and the cooling tower is placed in the reactor operation hall which with ventilation and air condition system. Therefore, the design conditions include failure of ventilation and air condition system. This section also gives the operating parameters of different input power (ie, different cooling capacity) in extreme temperature condition such as the failure of ventilation and air condition system. Finally, the section calculated the operating parameters of cool system supporting structure on the beyond design basis accident.

4.1 air condition is working and two pipelines operating.

Fig.5 shows the changes of the temperature parameters of air cooler and the temperature of the four supports as the environment temperature changes when the air condition is normal working and two pipelines operating synchronously.

As can be seen from the figure, when the environment temperature changes from -20 ~ 40 °C, the temperature in reactor hall changes from 16 °C to 35 °C, the inlet temperature of cooling water changes from 27.4 °C to 45.6 °C, and support wall temperature changes from 38.1 ~ 55.4 °C. The calculation results are far below the safety limits on normal working condition.

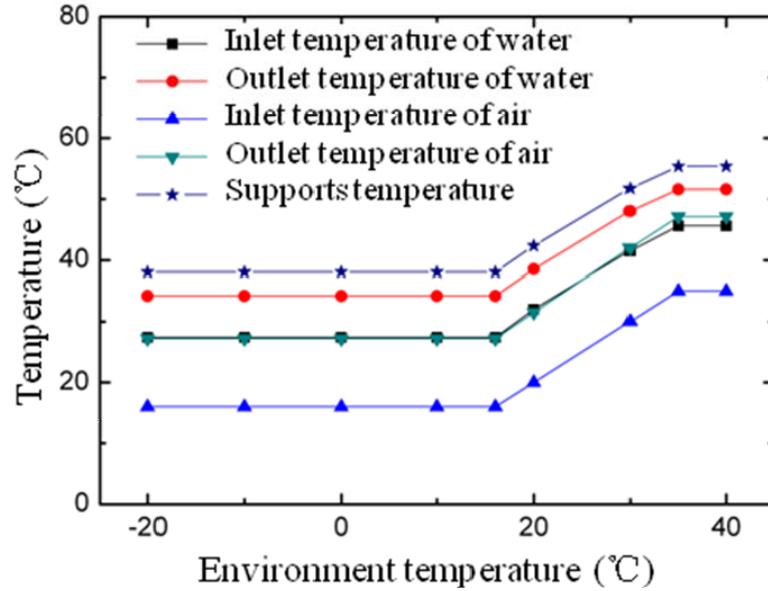


Fig.5 Calculation results(Air condition system is working and two pipelines operating)

4.2 air condition is working and one pipelines operating.

Fig.6 shows the changes of the temperature parameters of air cooler and the temperature of the four supports as the environment temperature changes when the air condition is normal working and only one pipelines operating .

As can be seen from the figure, when the environment temperature changes from -20 ~ 40 °C, the temperature in reactor hall changes from 16 °C to 35 °C, the inlet temperature of cooling water changes from 32.6°C to 51.7 °C, and support wall temperature changes from 50.7°C to 68.4°C. The calculation results are also below the safety limits on normal working condition.

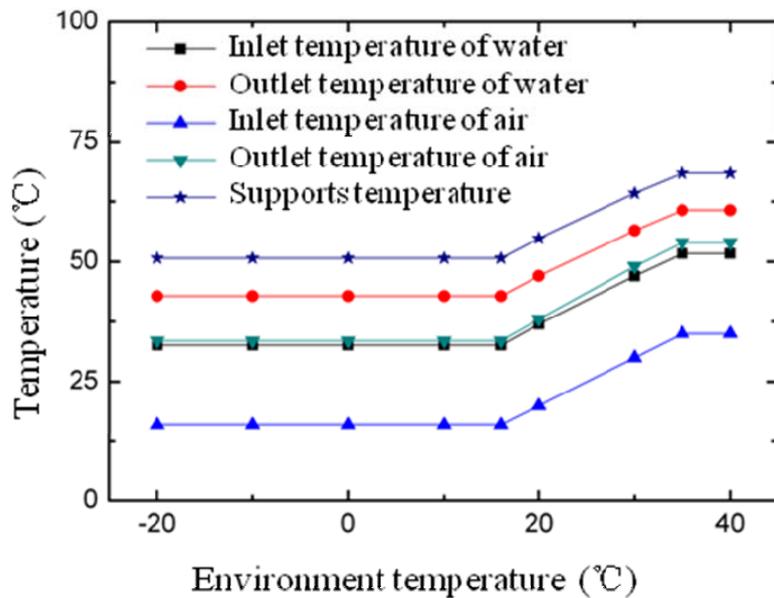


Fig.6 Calculation results(Air condition system is working and one pipelines operating)

4.3 air condition is broken and two pipelines operating.

Fig.7 shows the changes of the temperature parameters of air cooler and the temperature of the four supports as the environment temperature changes when the air condition is broken and two pipelines operating synchronously.

As can be seen from the figure, when the environment temperature changes from $-20 \sim 40$ °C, the temperature in reactor hall changes from 5 °C to 65 °C, the inlet temperature of cooling water changes from 16°C to 77 °C, and support wall temperature changes from 27.9°C to 86.2°C. The maximum temperature results are much higher than the above two conditions, but are still below the safety limits on normal working condition.

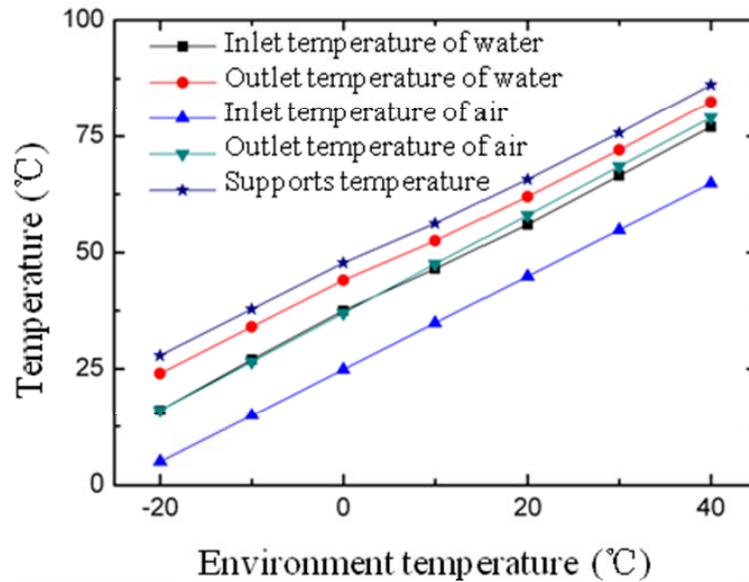


Fig.7 Calculation results(Air condition system is broken and two pipelines operating)

4.4 air condition is broken and one pipelines operating.

Fig.8 shows the changes of the temperature parameters of air cooler and the temperature of the four supports as the environment temperature changes when the air condition is broken and only one pipelines operating.

As can be seen from the figure, when the environment temperature changes from $-20 \sim 40$ °C, the temperature in reactor hall changes from 5 °C to 65 °C, the inlet temperature of cooling water changes from 24.5°C to 84 °C, and support wall temperature changes from 43.6°C to 99°C. The maximum temperature is higher than the result in 4.3, but are still below the safety limits on normal working condition.

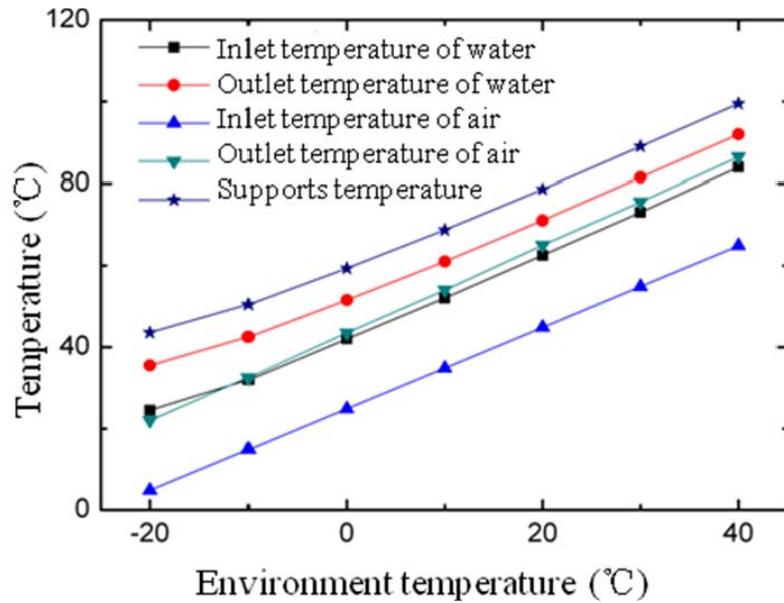


Fig.8 Calculation results(Air condition system is broken and one pipelines operating)

5. Conclusion

Reactor pressure vessel support cooling system is a passive safety system in HTGR. Thermal hydraulic analysis of this system was processed in this work. The calculation flow chart was shown. And the designed parameters of air cooler were analyzed. The operating parameters for four different working conditions were calculated. The results tell that even the worst working condition is below the safety limits.

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