Study on Limit Margin of Rising and Cooling Rate in Primary Circuit of CPR1000 Unit

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Abstract: The thermal conductivity of waste heat removal system of CPR1000 unit is analyzed, and the rate margin of primary circuit is studied. In this study, the design parameters of a domestic CPR1000 residual heat removal system are used to study the primary loop temperature margin according to the different core states, and the primary loop temperature margin according to the different valve openings of the residual heat removal system (RRA) . The results show that the CPR1000 unit has a large margin in cooling down, but there is no room for improvement in the process of heating up. Therefore, it is necessary for CPR1000 unit to enhance the effect of primary loop heating and cooling rate on primary loop thermal stress, material and control operation of system equipment.

Keywords: Primary circuit, heating and cooling, margin.

1. Introduction

The primary loop pipeline, pressure vessel and other equipment work in high temperature, high pressure and high radioactive conditions, with the change of operating conditions, their temperature, pressure changes. Temperature change will cause the contraction or expansion of metal material, the temperature stress will lead to thermal fatigue; pressure change will cause the corresponding internal stress of metal material, in addition to strength damage will lead to mechanical fatigue. In order to prevent the main equipment and pipelines of the primary circuit from being damaged because of exceeding the maximum applied stress of the material, the rate of pressure change and shutdown cooling rate of the primary circuit are limited. At present, the heating and cooling rate of CPR and its similar units in China is controlled below 28 ° C/H under normal operating conditions, and the heating and cooling rate of primary circuit is not over 56 ° C/H under transient and accident operating conditions.

During the normal shutdown of the unit, the cooling of the primary circuit consists of two parts, the evaporator completes the first stage of cooling, and the waste heat removal system completes the second stage of cooling, the cooling of the evaporator in the first stage can meet the requirements of any cooling rate of the primary circuit, in the second stage, the cooling capacity of the waste heat removal system will be controlled by the circulating flow rate of the waste heat removal system and the cooling water flow rate of the equipment, therefore, based on the design of CPR1000 waste heat removal system, combined with the different states of the core and the different states of the waste heat removal system equipment, this paper explores the limit margin of the primary loop heating and cooling rate, it lays a foundation for raising the limit value of primary loop heating and cooling rate.

2. Modeling and simulation of waste heat removal system

RRA includes pumps, heat exchangers, valves, pipes, flow measurement devices, etc. , as shown in Figure 1[2] . The hydraulic simulation model of RRA system in this paper is built by Flomaster software version V7.9

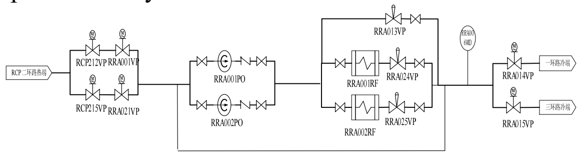

Fig. 1 RRA system diagram

2.1 Pump simulation

RRA pump is centrifugal pump. FloMASTER adopts dimensionless Suter characteristic curve input mode when using pump lift and torque characteristic curve. By creating the actual head-flow curve or torque-flow curve of pump, the dimensionless Suter of pump characteristic data can be realized automatically in FloMASTER. When fitting the pump characteristic curve, it can be processed in Excel, and the dimensionless data can be introduced into FloMASTER to customize the pump characteristic curve. The fitting curve of the pump is shown in Figure 2.

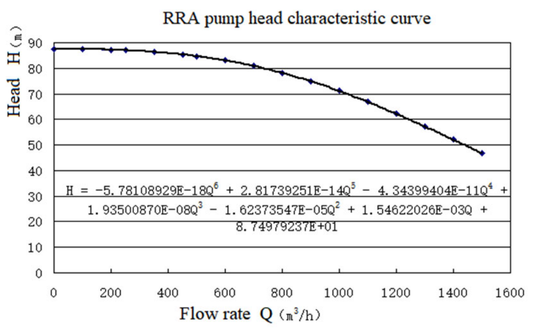

Fig. 2 RRA pump fitting curve and equation (1495rpm)

2.2 Valve emulation

For valves, the drag coefficient and flow coefficient are optional, meaning that only one of the two parameters needs to be defined. The drag coefficient and flow coefficient are calculated as [3] :

The resistance coefficient is calculated as:

$$K = 2 \cdot (P_i - P_o) \cdot \frac{A^2}{\rho \cdot Q^2}$$

Flow coefficient definition:

$$C_V = Q\sqrt{\frac{\rho}{\Delta P}}$$

Among them:
CV: flow coefficient;
Q: Volume Flow, M 3/s;
: fluid pressure loss through Valve, PA.
: density, KG/m 3
S: Valve section, M2
According to the system design calculation, the RRA system valve resistance coefficient and flow coefficient data as Table 1.

Table 1 RRA system valves detailed parameters

Valves	CV	Coefficient of resistance	Valve type
RRA001VP	7930	0.248	Gate valve
RRA002VP	10960	0.200	Gate valve
RRA003VP	10960	0.200	Gate valve
RRA004VP	2215	1.641	Check valve
RRA005VP	2215	1.641	Check valve
RRA006VP	6165	0.212	Gate valve
RRA007VP	6165	0.212	Gate valve
RRA008VP	6165	0.212	Gate valve
RRA009VP	6165	0.212	Gate valve
RRA010VP	6165	0.212	Gate valve
RRA011VP	6165	0.212	Gate valve
RRA013VP	2104 (max)	0.797	Butterfly valve (control valve)
RRA014VP	4315	0.280	Gate valve
RRA015VP	4315	0.280	Gate valve
RRA021VP	7930	0.248	Gate valve
RRA023VP	3915	0.230	Gate valve
RRA024VP	1768 (max)	1.129	Butterfly valve (control valve)
RRA025VP	1768 (max)	1.129	Butterfly valve (control valve)
RRA212VP	7930	0.248	Gate valve
RRA215VP	7930	0.248	Gate valve
RRA321VP	4180	0.620	Check valve
RRA121VP	4180	0.620	Check valve

2.3 Pipeline simulation

2.3.1 Straight pipe simulation

The straight pipe resistance model is based on the internationally accepted Clobroke-White formula.
The formula is:
Laminar flow region (RE ≤2000) :

$$f = f_l = \frac{64}{Re}$$

Transition flow (2000 < Re ≤4000) :

$$f = x \cdot f_t + (1 - x) \cdot f_l$$

Turbulence (Re > 4000) :

$$f = f_t = \frac{0.25}{\left[\log\left(\frac{K}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2}$$

Of which,
for laminar resistance coefficient;
Turbulence resistance coefficient;
For a coefficient, its formula is:

$$x = \frac{Re - 2000}{2000}$$

Re is Reynolds number;
D for pipe inner diameter, M;
K is the coefficient in Darcy's resistance formula, and it depends on the roughness.

2.3.2 Elbow simulation

The local resistance coefficient of the elbow is related to the actual elbow radius and the inner diameter of the pipe, including three parts: the resistance caused by the deployment length, the resistance caused by the secondary flow, and the resistance caused by the obstruction of the downstream straight pipe [4] , the equivalent length of the 90 ° elbow and the elbow radius are tabulated as follows:

Table 2. 90 ° elbow equivalent length versus elbow radius

R/D	1	1.5	3	4	6	8	10	14
L/D	20	14	12	14	17	24	30	34

Local resistance coefficient of other bends.
When Re > 104, FloMASTER calculates the K value of the elbow resistance coefficient as follows:

$$K = K_b C_{Re} C_f$$

Style,
uncorrected elbow loss coefficient, dimensionless; , generated by software based on user input R/D, bending angle values, as shown in Figure 3.

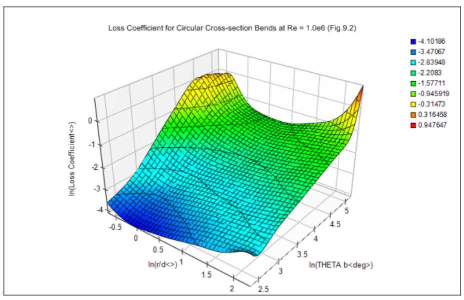

Fig. 3 elbow resistance coefficient

:Elbow turning radius/section inner diameter, dimensionless;
Bending angle of elbow, unit ° ;
: Reynolds Number Correction Factor, r/D value based on user input and software-calculated Re value.

2.3.3 Connector simulation

Taper (burst)
At that time,

$$k_{\text{go out}} = 0.8\sin(\frac{\theta}{2})[1\text{-}(\frac{D_{\text{go out}}}{D_{\text{enter}}})^2]$$

at that time,
Gradual expansion (sudden expansion)
At that time,

$$k_{\text{enter}} = 2.6\sin(\frac{\theta}{2})[1\text{-}(\frac{D_{\text{enter}}}{D_{\text{go out}}})^2]^2$$

At that time,

$$k_{\text{enter}} = [1\text{-}(\frac{D_{\text{enter}}}{D_{\text{go out}}})^2]^2$$

the drag coefficient of the size of the head relative to the entrance.

Table 3 Connector data for RRA circuit of which

Size Head model	Inside diameter mm	Inside diameter of small head mm	Length MM	Angle θ °
10-8”	247.6	193.6	178	17.25
12-10.”	298.6	247.6	203	14.32
12-8”	298.6	193.6	203	29.00

D into: inlet tube inner diameter, MM;
D Exit: exit tube inner diameter, MM;
K outlet: outlet tube resistance coefficient;
K-in: inlet tube resistance coefficient;
: Zhang Jiao, ° .
1.4 heat exchanger simulation
Assuming that the fluid resistance characteristics of the heat exchanger meet the equation, and the resistance coefficient is constant, then according to the design has
= 11.65(130 ° C for water density) .

Table 4rra heat exchanger thermal and hydraulic characteristics

Parameter	Shell side	Tube side	Unit
Density ρ	992.72	987.29	KG/m 3
Mass flow rate g	275.76	249.56	KG/s
Constant pressure specific heat capacity CP	4.17	4.17	KJ/(kg. ° C)
Heat Transfer Q	10366.07	10413.61	kW
P	0.4		
R	0.9		
The correction coefficient ψ	0.935		
Mean temperature and pressure δtm	12.45		℃
Heat transfer coefficient K	2167.35		W/(° C.M2)

The heat transfer coefficient of the shell side can be considered constant if the RRI water supply flow rate is constant and the water supply temperature is 25 ° C. According to the thermodynamic and hydraulic characteristics of the heat exchanger in table 4, considering the influence of the flow rate on the heat transfer coefficient, the outlet temperature of the heat exchanger varies with the inlet temperature and flow rate, as detailed in Figure 4.

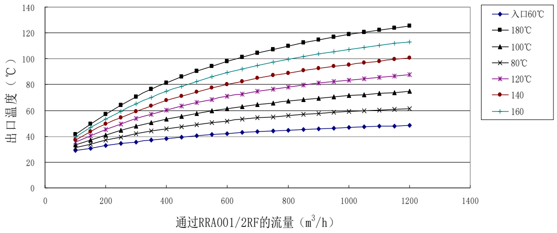

Figure 4. Rra001/002RF heat exchanger characteristic curve

3. Calculation of heating and cooling rate limits

The unit is heated by the main pump and the regulator heater in the first loop before reaching the critical point. During the heating process, there are three working conditions of core power, which are detailed in table 5:
A) Operation Mode 1: the core power is zero power, simulating the heating condition of all new fuel rods entering the reactor for the first time;
B) condition 2: the core power is two-thirds of the decay heat after 30 days of shutdown and one-third of the core reload, so only two-thirds of the old fuel rods that have not been replaced have decay power during the heating process;
C) condition three: the core power is the decay heat condition corresponding to the 30-day shutdown, and the envelope condition two may have the uncertain influence.

Table 5. Power setting for heating conditions

Power setting	Actual Power/MW
Zero power	0
The 30-day shutdown corresponds to two-thirds of the decay heat	3.03
30 days' decay heat	4.55

According to the simulations:
A) the higher the core power is, the faster the primary coolant temperature rises, in which the core power is the decay heat condition corresponding to the 30-day shutdown, and the primary coolant temperature rise rate is the fastest, as shown in figure 5. During the whole heating process, the maximum heating rate of the three operating conditions is less than 56 ° C/H;
B) during the heating process, the heating rate is relatively high when the average temperature of the primary coolant is below 100 ° C. When the average temperature of the first circuit is higher than 100 ° C, part of the coolant will

be vaporized from the liquid phase to the gas phase in the Second Circuit
C) when the average temperature of the primary coolant rises to 140 ° C, the air chamber is built and the volume of primary water decreases, so the heating rate of the primary coolant increases slightly
D) when the average temperature of the primary coolant rises to 180 ° C, the RRA pump stops, and the RRA system exits, which makes the total heat production of the primary coolant slightly decrease, thus making the heating rate of the primary coolant slightly decrease;
E) the subsequent decrease in the rate of coolant heating is due to a gradual increase in the rate of coolant flow on the secondary side as the natural circulation on the secondary side is established. It is beneficial for the temperature stratification of the secondary side coolant to disappear gradually and get more and more full agitation, and the heat transfer of the primary and secondary side will also be enhanced, so the average water temperature of the primary circuit coolant rises more and more slowly.

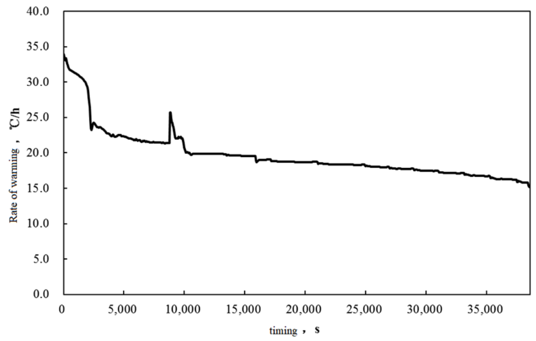

Fig. 5 Operating condition 3, the heating rate of the primary loop

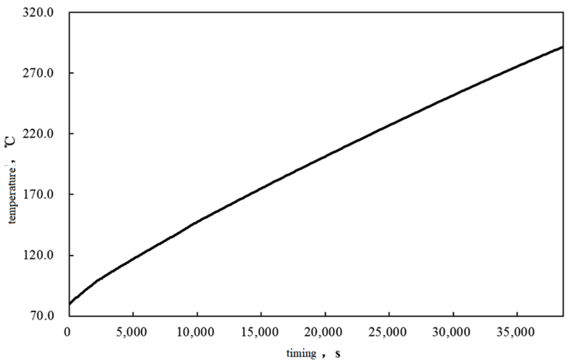

Fig. 6 The change of the average temperature of the first circuit under condition 3

Steam generator can meet any cooling requirements of the first circuit, so this study is mainly aimed at the situation after RRA connection.
When the RRA024/025/013VP valve is fully opened and the RRA013VP is fully closed, the cooling rate of the primary loop is the highest.
During the cooling process, the core is set according to the actual core power as shown in Table 6.

Table 6. Cooling process power setting

Time (h)	Nuclear Power (% FP)	Write program power (W)
24	0.0061	1.766E + 07
48	0.00492	1.424E + 07
96	0.00384	1.112 E + 07
192	0.00284	8.222E + 06
360	0.00213	6.166E + 06
720	0.00157	4.545E + 06

According to the simulations:
During the cooling process, the temperature difference between the two sides of the RRA heat exchanger decreases with the decrease of the primary-loop coolant temperature, which makes the heat transfer power of the heat exchanger decrease gradually, and the core decay power also decreases gradually, therefore, the cooling rate of the primary coolant decreases
When the regulating valve RRA024/025VP is fully opened and the RRA013VP is fully closed, the cooling rate is the maximum, and the first circuit can exceed 28 ° C/H when it is above 100 ° C, as shown in Figs. 7 and 8.

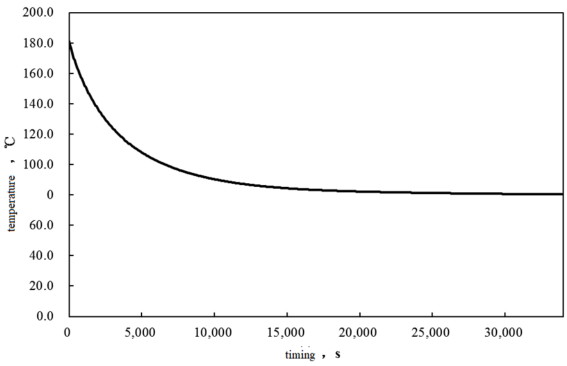

Fig. 7 Change in the average temperature of the primary coolant

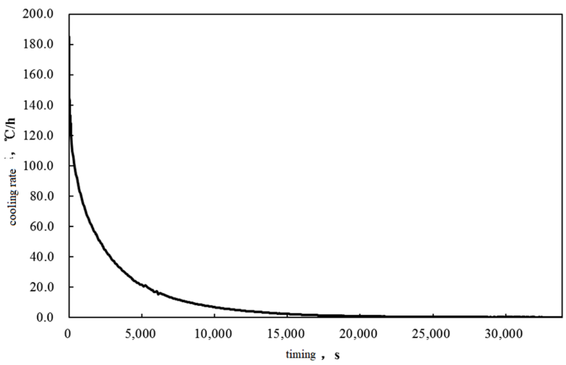

Fig. 8 Cooling rate of primary circuit

4. Conclusion

In this paper, a CPR1000 unit as a prototype, the study of RRA connection when the capacity of the primary loop temperature, the following conclusions:
CPR1000 unit does not improve the margin during the heating process;

CPR1000 unit has a large cooling margin when the average temperature of the first circuit is above 100 ° C, and no increasing margin when the average temperature of the first circuit is below 100 ° C

Thermal stress analysis and unit control evaluation are also needed to improve the limit of primary loop heating and cooling rate.

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