Thermal-hydraulic Design and Transient analysis of Passive air cooling system for CPR1000 spent fuel storage pool

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Abstract

After the Fukushima nuclear accident in 2011, the safety of the spent fuel pool (SFP) which lost the cooling function and feed water suffered an unprecedented threat. Many countries paid attention to the safety of the SFP. Researches on improving the safety of the SFP have become the important topic. In China analyzing and improving the safety of the SFP for CPR1000 is one sub-topic of them.

This paper gives a design of passive air cooling system for CPR1000 SFP, which can control the water temperature of the SFP under 80℃. Then the transient analysis of the CPR1000 SFP with designed passive air cooling system will be done in station black out (SBO) accident by the best-estimate thermal-hydraulic system code RELAP5.

The design calculation results show that to maintain the temperature of CPR1000 SFP under 80℃, the tube numbers of the SFP and air heat exchangers are 6627 and 19086 respectively. The height difference between the bottom of the air heat exchanger and the top of the SFP heat exchanger is 3.8m. The SFP heat exchanger's tube number decreases as the height difference increases, while the air heat exchanger's tube number increases.

The transient analysis results show that after the SBO accident, a stable air cooling natural circulation is established. The surface temperature of CPR1000 SFP increases continually until 80.5 ℃, which indicates that the design of the passive air cooling system for CPR1000 SFP is capable of removing the decay heat to maintain the temperature of the SFP around 80℃ after losing the heat sink.

Keywords: CPR1000, passive cooling system, RELAP5, SBO, SFP

Nomenclature	
k	Total heat transfer coefficient ($W/(m^2 \cdot K)$)
d_i	Tube inner diameter (m)
d_o	Tube outside diameter (m)
h_i	Tube inner heat transfer coefficient ($W/(m^2 \cdot K)$)
h_o	Tube outside heat transfer coefficient ($W/(m^2 \cdot K)$)
η_f	Heat rejection efficiency of fins
λ	Heat conduction coefficient ($W/(m \cdot K)$)
A_i	Total internal surface area of the heat exchanger (m^2)
A_h	Total external surface area of the heat exchanger (m^2)
A_f	Total surface area of the fins (m^2)
A_r	External surface area except the fin surface area (m^2)
Φ	Heat transfer power (W)
ΔT_m	Logarithmic mean temperature difference
Nu	Nusselt number
Gr	Grashof number
Pr	Prandtl Number
g	Gravitational acceleration (m/s^2)
l	Tube length(m)
α_v	Expansion coefficient ($1/K$)
v	Kinematic viscosity (m^2/s)
T_w	Wall temperature (K)
T_∞	Water average temperature (K)
H	Height of the interlayer (m)
δ	Thickness of the interlayer (m)
f	Friction factor
De	Equivalent diameter (m)
u	Fluid velocity (m/s)
A_1	Upstream area (m^2)
A_2	Downstream area (m^2)
F_t	Structure correction factor
N_s	The number of serial heat exchangers
N_p	The number of tube passes
T_{in}	Inlet temperature of the heat exchanger(°C)
T_{out}	Outlet temperature of the heat exchanger(°C)
T_i	Inner tube wall temperature of the heat exchanger(°C)
T_o	Outer tube wall temperature of the heat exchanger(°C)
G	Mass flow of the passive cooling loop (kg/s)
Q	Decay heat(MW)

1. Introduction

The spent fuel pool (SFP) is one of the most important equipment in the nuclear power plant. It plays a major role in removing the decay heat and shielding the radiation produced by the spent fuel during the process of spent fuel storage. After the Fukushima nuclear accident in 2011, investigations on the thermal-hydraulic characteristics and the safety performance of the spent fuel pool have become the research focus in the world.

In 2012, China promulgated an 863 project named "nuclear safety research". One of the sub-topics is aimed to analyze and improve the safety of the spent fuel pool for generation II+ pressurized water reactor, such as CPR1000 which is the major reactor type in service or in construction in China. However, the cooling system of the SFP for generation II+ PWR is depending on the driving forces. Once without the driving forces, the water of the SFP will be boiling and the fuel will be melt. The passive safety systems were put forward in the 1980s, which depend on the gravity and natural circulation instead of operator actions or electronic feedback in the emergency event. The passive system has been widely applied in generation III reactors, such as the Westinghouse AP1000[1], the Japanese N.G.P, the Chinese ACPR1000[2], the Russian VVER, the PIUS with inherent safety features designed by ABB Power Generation Ltd. in Switzerland[3], the PWR with SIP-1 presented by SIET laboratory in Italy[4], and so on.

After Fukushima accident, a number of researchers have studied the safety of the spent fuel pool. Carlos et al. used TRACE thermal-hydraulic code to simulate the steady state and transient conditions with a loss of cooling and coolant of spent fuel pools. Their calculations of steady state have a good agreement with the measurements of Maine Yankee[5]. Chen et al. have developed a 3-D CFD model to analyze the localized distributions of the flow and heat transfer of the spent fuel pool in a loss of cooling event. The results show that the temperature rising rate calculated by the 3-D CFD is the identical to that calculated by Procedure 597.1 for the Maanshan NPP[6]. Wang et al. applied RELAP5 to investigate the behavior of the spent fuel pool for CPR1000 with loss of heat sink[7].

Some researchers have developed the advanced passive safety system for SFP. Arndt B et.al[8] introduced a design based on the concept of cooling the spent fuel storage pool only depending on air cooling. Westinghouse Corporation[9] designed a floating passive cooling system using gravitate heat pipe principle to manage the spent fuel pool cooling. Their system is composed of many modular gravitate heat pipes. Each heat pipe may at most remove 300 kW of heat, and the cooling system can control the temperature of the pool water under 60℃. Shanghai Jiao Tong University et.al[10] designed a passive cooling system for spent fuel pool of CAP1400. Their cooling system adopts separate heat pipe principle, and removes the decay heat of spent fuel to atmospheric environment depending on the air cooling tower. This passive cooling system can keep the pool water from boil, even under station blackout (SBO).

In the present paper, a passive cooling system for the spent fuel pool of CPR1000 is designed to control its water temperature under 80℃. The safety performance of the spent fuel pool with passive cooling system is analyzed under station blackout using RELAP5 code. The research of this paper is useful for the safety improvement of CPR1000 spent fuel pool system.

2. Thermal-hydraulic design of passive cooling system

The CPR1000 (improved Chinese PWR) which is based on the French 900MW PWR with upgraded net power output of 1000 MW is the main reactor type in service and under construction in China. So its safety behavior is a very important issue for Chinese nuclear industry.

When SBO accident takes place, the spent fuel storage pool water temperature will continue to rise until boiling. If no active cooling measures are available, the water will evaporate away. Then the radioactive materials will release into the environment to cause danger. The passive cooling system is applied to remove the decay heat effectively and control the water temperature below an acceptable level when the active devices failure or loss of heat sink occurs.

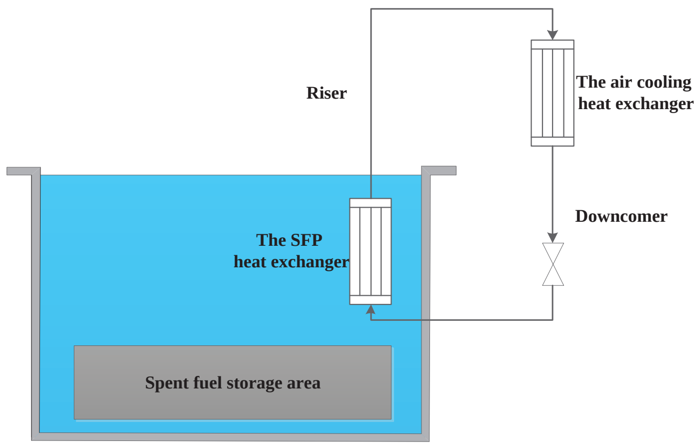

Fig. 1 Design diagram of passive cooling system

The sketch of the designed passive cooling system is shown in. Fig. 1 The heat exchangers in the SFP and air are all shell and tube type. The SFP heat exchanger is immersed in the pool around the pool wall to load or unload the spent fuels assemblies conveniently. Water is used as the working fluid in the closed loop. The atmosphere is used as the final heat sink. The air cooling heat exchanger is equipped with uniform section circular fins to increase the heat transfer area.

Under normal operating conditions, the tube side of the heat exchangers and the connecting pipes are filled with water and isolated by a check valve and an isolation valve. After the SBO occurs, the check and isolation valves will open automatically and the passive cooling system will start to work automatically without any active operation. The water heated in the SFP heat exchanger flows upward and enters the tube side of the air cooling heat exchanger, where it is cooled by the shell side air by natural convection. Finally, the cooled water flows back to the tube side of the SFP heat exchanger by gravity. Consequently, the passive SFP cooling system removes the decay heat by natural circulation under station blackout accident.

2.1 The heat transfer model in the passive cooling system

Ignoring the fouling resistance, the total heat transfer coefficient correlations for SFP and air heat exchangers based on tube outer surface are respectively as

$$\frac{1}{k}=\frac{1}{h_i}\frac{d_o}{d_i}+\frac{d_o}{2\lambda}\ln\frac{d_o}{d_i}+\frac{1}{h_o} \tag{1}$$

$$\frac{1}{k}=\frac{A_h}{h_i A_i}+\frac{A_h}{2\pi\lambda l}\ln\frac{d_o}{d_i}+\frac{A_h}{h_o\left(A_r+A_f\eta_f\right)} \tag{2}$$

In Eq.(2), η_f is the heat rejection efficiency of fins, and can be found according to the fin efficiency curve[11]; A_i, A_h is the total internal and external surface area; A_f is the fin surface area; A_r is the external surface area except the fin surface area, $A_h = A_r + A_f$.

The heat transfer equation is as following form:

$$\Phi = kA_t \Delta T_m \tag{3}$$

In Eq.(3), ΔT_m is the logarithmic mean temperature difference and it can be expressed by

$$\Delta T_m = \frac{\Delta T_{\max} - \Delta T_{\min}}{\ln \frac{\Delta T_{\max}}{\Delta T_{\min}}} \tag{4}$$

The heat transfer coefficient between the wall and water in the tubes of the SFP or air cooling heat exchanger is calculated by Churchill-Chu correlation[12]:

$$\mathrm{Nu} = [0.825 + \frac{0.387(\mathrm{Gr} \times \mathrm{Pr})^{1/6}}{[1 + (\frac{0.492}{\mathrm{Pr}})^{9/16}]^{8/27}}]^2 \tag{5}$$

Where,

$$\mathrm{Nu} = \frac{hl}{d} \tag{6}$$

$$\mathrm{Gr} = \frac{g\alpha_V |T_w - T_\infty| l^3}{\nu^2} \tag{7}$$

For the heat exchanger without fins, the heat transfer mode between the tube outer wall and the coolant belongs to natural convection in infinite space. For the heat exchanger with fins, the heat transfer mode may belong to natural convection in infinite space or natural convection in finite space depending on the situation. Seigel R et al.[13] found if the ratio of the fin pitch to fin height is larger than 0.28, the heat transfer mode between the fins and the coolant is natural convection in infinite space. Otherwise, it will be natural convection in finite space. The natural convection heat transfer correlation in infinite space is as follows[11]:

$$Nu = C(Gr * \mathrm{Pr})^n \tag{8}$$

The natural convection heat transfer correlations in vertical and horizontal finite space can be presented respectively as follows[11]:

$$Nu = C(Gr * \mathrm{Pr})^n \left(\frac{H}{\delta}\right)^m \tag{9}$$

$$Nu = C(Gr * \mathrm{Pr})^n \tag{10}$$

Eq. (10) is fully applicable to gas. But for liquid, considering the relation between the properties and the temperature, the right side of this equation should be multiplied by a correction factor depending on the property change. So the heat transfer correlation for the tube outside is modified as

$$Nu = C(Gr * \mathrm{Pr})^n \left(\mathrm{Pr}_f / \mathrm{Pr}_w\right)^{0.11} \tag{11}$$

In the Eq. (8)-(11), C, n and m are determined by experiments, depends on the heat transfer surface shape and position, turbulent or laminar flow, and thermal boundary conditions. Their values can be found in the literatures[11].

2.2 The pressure drop model in the passive cooling system

The establishment of the stable natural circulation is based on the situation that the pressure drop produced by the density difference between the riser and downcomer must overcome the resistance pressure drop in the loop:

$$\Delta P_{el} = \sum \Delta P_f + \sum \Delta P_{c,s} + \sum \Delta P_{c,c} + \sum \Delta P_{c,e} + \sum \Delta P_t \quad (12)$$

Where,

The elevation pressure drop:

$$\Delta P_{el} = P_{down} - P_{up} \quad (13)$$

The frictional pressure drop:

$$\Delta P_f = f \frac{l}{D_e} \frac{\rho u^2}{2} \quad (14)$$

The elbow, junction or valve pressure drop:

$$\Delta P_{c,s} = K \frac{\rho u^2}{2} \quad (15)$$

The area abrupt contraction pressure drop:

$$\Delta P_{c,c} = 0.4[1 - (\frac{A_2}{A_1})^2] \frac{\rho u_2^2}{2} \quad (16)$$

The area abrupt expansion pressure drop:

$$\Delta P_{c,e} = (1 - \frac{A_1}{A_2})^2 \frac{\rho u_1^2}{2} \quad (17)$$

The heat exchanger tube pressure drop:

$$\Delta P_t = (f \frac{l}{D_e} + 3) F_t F_s N_p \frac{\rho u_3^2}{2} \quad (18)$$

Where, K is form drag coefficient， F_t is structure correction coefficient with the value of 1.4 for the $\phi 25 \times 2.5$ pipe.

2.3 Thermal-hydraulics design

According to the design basis of the spent fuel pool for CPR1000, the max permissible temperature of the pool water is 80 ℃. In this paper, 80℃ is designed as the final temperature of the spent fuel pool in a loss of heat sink event. The environment temperature is designed to 30 ℃. According to the target, the tube numbers N of the SFP and air cooling heat exchangers and the height difference Δh between the top of the SFP heat exchanger and the bottom of the air cooling heat exchanger are calculated by other designed parameters.

The designed geometrical parameters of the passive cooling system are shown in Table 1. The last step is to calculate by the mass flux G and the pressure drop of the passive cooling loop. The detailed calculation procedure is shown in Fig. 2.

Table 1 Geometrical parameters of the passive cooling system

SFP heat exchanger	Air cooling heat exchanger

Tube length / m	Tube type	Tube length / m	Tube type	Fin height /m	Fin thickness / m	Fin distance / m
6.5	ϕ25×2.5	12.0	ϕ25×2.5	0.03	0.002	0.01

Other parameters of the passive cooling system are assumed as Table 2. The power of the spent fuel assemblies is set to 11.98MW , which is the max imum power in abnormal conditions.

Table 2 Other assumed parameters of the passive cooling system

Parameter	Unit	Value
Environment temperature	℃	30
Pool temperature	℃	80
Inlet temperature of the SPF heat exchanger	℃	35
Mass flow of the passive cooling loop	$kg{\cdot}s^{-1}$	65
Diameter of the passive cooling loop pipe	m	0.3
Power of the spent fuel assemblies	MW	11.98
Working fluid	/	Water

The tube number of each heat ex changer and height difference between the two heat exchangers are calculated by the design parameters, as shown in Table 3.
The height difference is 3.8m, which is easy to achieve from the view of engineering. These results indicate the d esigned passive cooling system for the spent fu el pool of CPR 1000 i s practical significance.

Table 3 The steady state results of the passive cooling system

Parameter	Unit	Value
Tube number of the SPF heat exchanger	/	6627
Tube number of the air heat exchanger	/	19086
Height difference	m	3.8

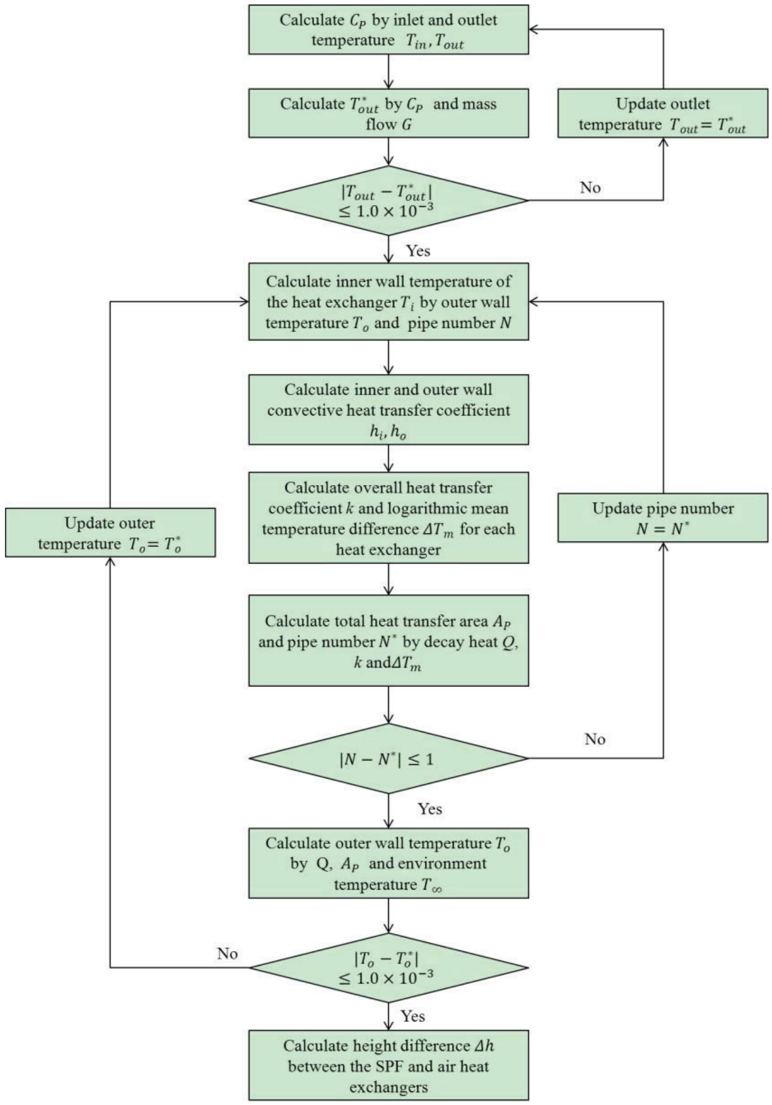

Fig. 2 Calculation flow chart of the passive cooling system

2.4 Height difference sensitivity analysis

As shown in section 2.3, the establishment of the stable natural circulation is based on the situation that the pressure drop produced by the density difference between riser and downcomer must overcome the resistance pressure drop of the loop. So the height difference between the bottom of the air heat exchanger and the top of the SFP heat exchanger which has the significant influence on pressure drop will affect the stable natural circulation.
Keeping other parameters constant, the tube numbers of the air and SPF heat exchangers are changed with the height difference between the bottom of the air heat exchanger and the top of the SFP heat exchanger. Fig. 3 and Fig. 4 show the curves of tube numbers of the air and SFP heat exchangers with the height difference, respectively. As they show, the SFP heat exchanger's tube number decreased as height difference increased， while the air heat exchanger's tube number increased.

This is because the mass flow of the natural circulation increases with the height difference. According to Eq.(19) ,

$$Q = C_p G \left(T_{out} - T_{in} \right) \tag{19}$$

where the decay heat Q and inlet temperature T_{in} is designed to be a constant, so T_{out} decreases with the increase of the height difference. This leads the logarithmic mean temperature difference of the SFP heat exchanger increases and the logarithmic mean temperature difference of the air cooling heat exchanger decreases. Final it results the heat transfer area of the SFP heat exchanger decreased and the heat transfer area of the air cooling heat exchanger increases as height difference increased shown from Eq.(3).

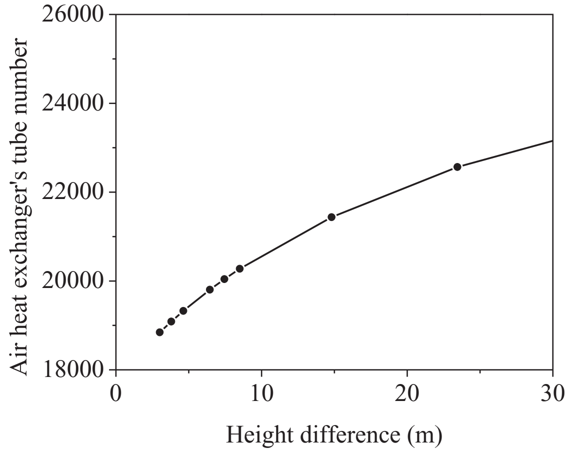

Fig. 3 The curve of tube number of the air heat exchanger with height difference

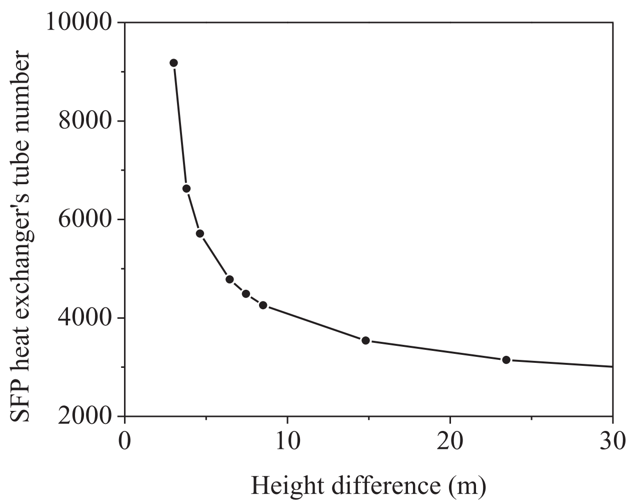

Fig. 4 The curve of tube number of the SFP heat exchanger with height difference

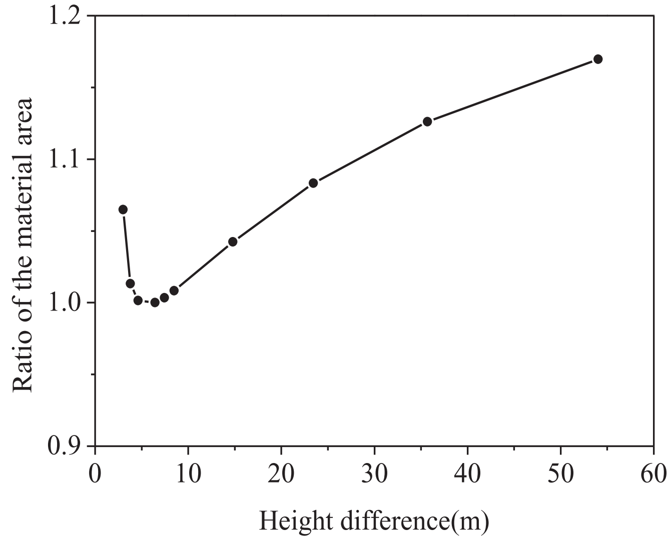

Fig. 5 The curve of the material area with height difference

The ratio of the material area is defined as the ratio of the material area of the passive system and the minimum of them. Fig. 5 shows the curve of the ratio of the material area with height difference. In terms of economy, the height difference is better between 3 to 10 meters.

3. The passive cooling system performance analysis based on RELAP5

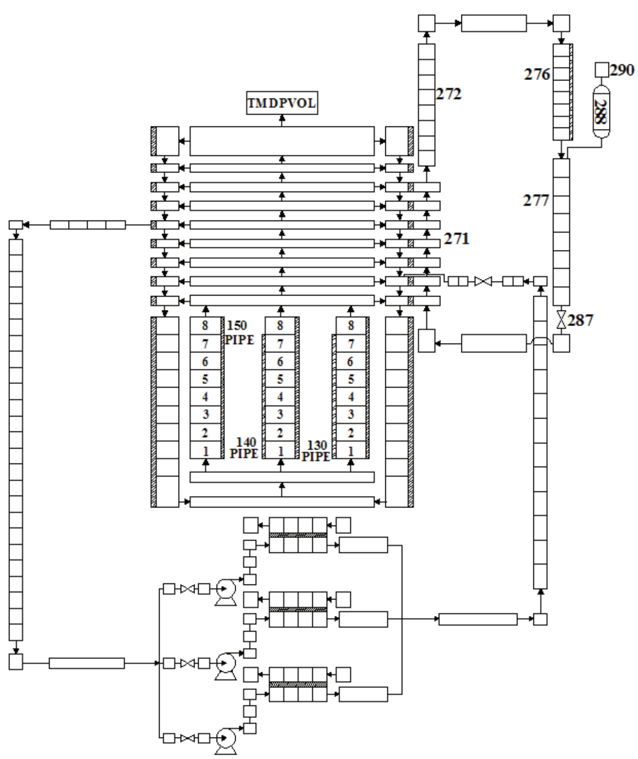

Fig. 6 Nodalization of the passive cooling system

This section will use RELAP5 to analyze the designed passive cooling system, taking the result of section 2 as the input conditions. We need to verify whether the passive cooling system can control the pool temperature at 80℃ after loss of heat sink occurs.

A nodalization of the passive cooling system for the SFP is shown in Fig. 6. Control volume 271 and 276 represent the SFP and air cooling heat exchangers respectively. Control volume 272 and 277 represent the riser and downcomer of the loop respectively. 287 is the valve at the downcomer, and must be opened immediately to remove the decay heat when the loss of heat sink occurs.

Fig. 7 shows the coolant mass flow change of the passive cooling system. The mass flux increases rapidly to 46.3 $kg{\cdot}s^{-1}$ at 100 seconds after the accident. Early in the accident the large temperature difference between the SFP and air heat exchangers causes the large density difference and a large driving force in the loop.

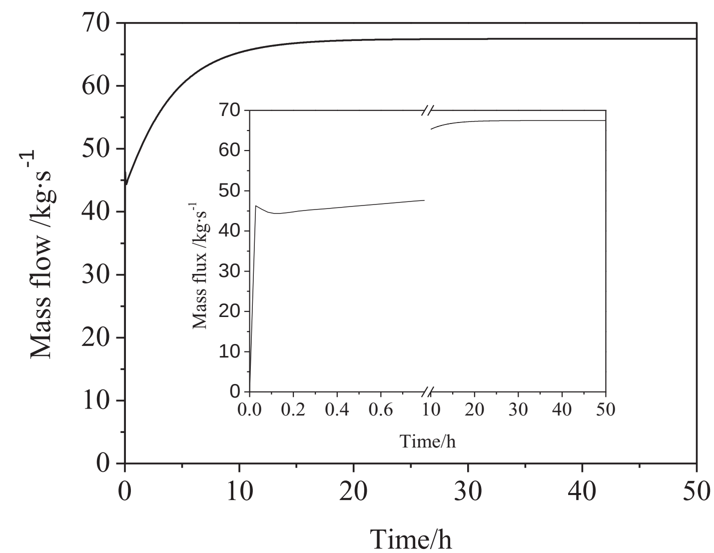

Fig. 7 The coolant mass flux change of the passive cooling system

As Fig. 8 shows, early in the accident the thermal load of the heat exchanger rises rapidly, but still under the decay heat of the spent fuel (11.98 MW). So the passive cooling system can't remove the decay heat, and the temperature of the pool surface increases continually, shown in Fig. 9.

The increase of the water temperature results in a larger temperature difference between the cold and heat sources of the loop. Moreover, the driving force of the coolant increases, and the coolant mass flux increases with it. Meanwhile the heat load of the heat exchanger increases until 11.98 MW to remove the decay heat of the spent fuel exactly. After that every parameter remains constant. It means the passive cooling system has been established successfully.

As shown in Fig. 9, the temperature of the pool surface is 80℃ after the establishment of the passive system. Fig. 10 shows the inlet temperature of the SFP heat exchanger is 35℃. They certifie the passive cooling system we designed is effective.

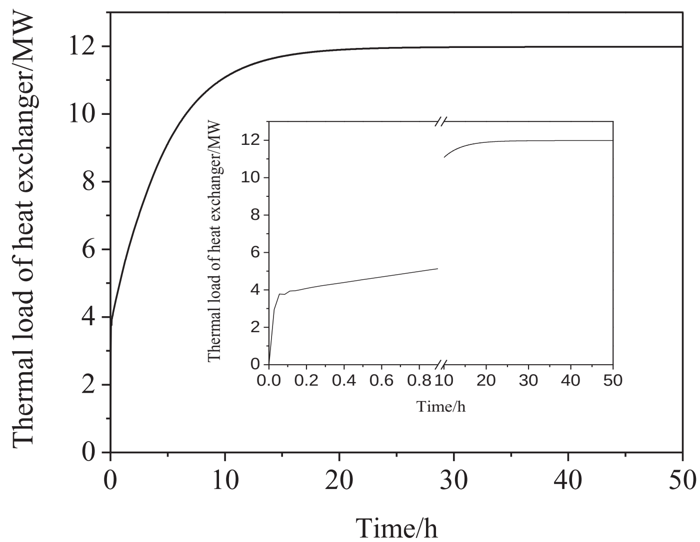

Fig. 8 The thermal load change of the heat exchanger

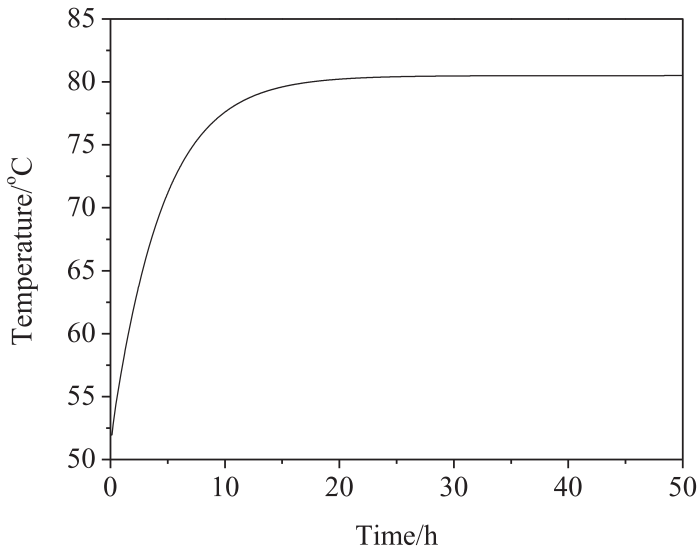

Fig. 9 The temperature profile of the pool surface

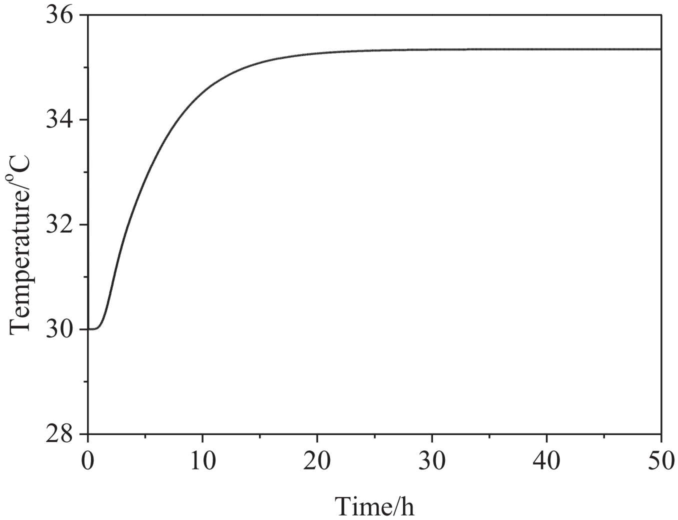

Fig. 10 The inlet temperature of the SFP heat exchanger

4. Conclusion

In this paper, a passive cooling system for the SFP of CPR1000 is designed. The passive cooling system can maintain the temperature of the SFP around 80℃ after losing heat sink. Then the height difference sensitivity was analyzed. The result shows that the SFP heat exchanger's tube number decreased as height difference increased, while the air heat exchanger's tube number increased.

The loss of heat sink accident of the spent fuel storage pool with the passive cooling system was analyzed by RELAP5-MOD3.3, which used the theoretical calculation as the input. After the accident, the temperature of the pool surface increased continually until 80.5℃. The result suggests that the design of the passive cooling system of the SFP for CPR1000 is successful to remove the decay heat to maintain temperature of the SFP around 80℃ after losing the heat sink. The present results will be useful for the improvement of the CPR1000 spent fuel pool cooling system.

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