

The comparison between the direct and second side passive residual heat removal system, and system optimized

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Abstract: The Passive Residual Heat Removal System (PRHRS) is always connected to the steam generator which is designed and prepared for the Station Black-out (SBO) accident. If the PRHRS is required to replace the active residual heat removal system, the system based on the primary loop of PWR would be the better choice. A PRHRS based on the primary loop of PWR (PL-PRHRS) is proposed and analyzed in this paper. Start-up and long-term characteristics of the PL-PRHRS are compared with the PRHRS based on the secondary loop of PWR (SL-PRHRS) by the safety analysis software Relap5/MOD4.0. To optimize the long-term operate performance of PL-PRHRS, a Two Phase Closed Loop Thermosyphon (TPCLT) is introduced to the system and simulated by conjugate boundary method for coupling the system with Relap5/MOD4.0. Results show that the decay heat could be removed continuously from the core in the SBO or other non-LOCA accidents by the PL-PRHRS. Comparing with the SL-PRHRS, the decay heat transfer of PL-PRHRS is established slower, but the decrease of coolant temperature is faster. Although the system could remove the decay heat in the long-term operation, its function is strongly dependent on the water volume in the tank. The introducing of TPCLT reduces the dependence radically so that the volume of the tank could be optimized during the design and higher inherent reliability would be achieved, especially when the tank is shared by other safety systems.

Keyword: PL-PRHRS; characteristics comparison; TPCLT; optimize

1. Introduction

A lot of Passive Residual Heat Removal Systems (PRHRS) have been used in the advanced pressure water nuclear reactor because of their high inherent reliability. Traditional design of PRHRS always connects the system to the second loop of PWR which is prepared for the Station Black-out (SBO) accident^[1-2]. But when the natural circulations of primary loop couldn't be established or the SGs lose its capabilities. The system can't work effectively. Even in the accident of SBO, the second loop design couldn't replace the active heat removal system thoroughly in the long-term operation because of the high thermal resistance. A PRHRS based on the primary loop is designed in AP1000 with a huge water tank as the heat sink which is also shared by the Safety Injection System (SIS)^[3].

But the different effects of the two methods on the primary loop have not been fully compared and need more research. On the other hand, the shared design means the functions of SIS and PRHRS are limited by the water volume in the tank, which maybe lack in the long-term operation. So measures should be taken to reduce the PRHRS's dependence on the water volume in the water tank.

So in this paper, a PRHRS based on the primary loop (PL-PRHRS) is designed and analyzed by the widely used software Relap5/MOD4.0 at first. Then the characteristics of start-up and long-term operation of PL-PRHRS and the PRHRS based on the second loop (SL-PRHRS) are compared. At last, a Two Phase Closed Loop Thermosyphon (TPCLT), which is simulated by conjugate boundary method, is introduced

and studied to reduce the system's dependence on the water volume in the tank.

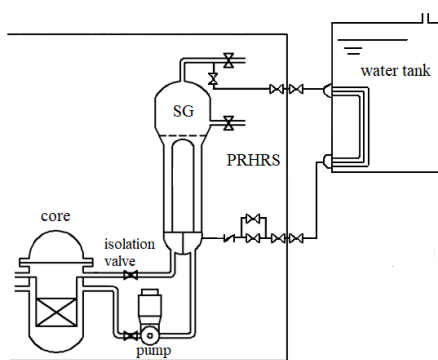
2. Description of the model

2.1 Brief description of PL-PRHRS

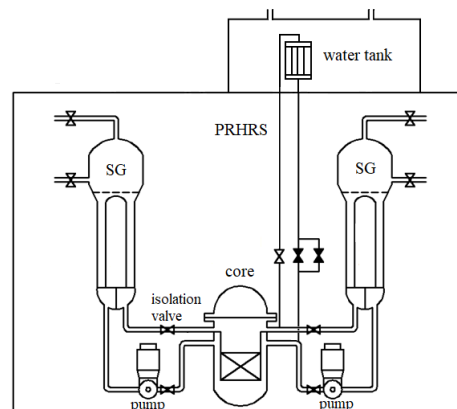
The design of PL-PRHRS is based on the Qinshan I nuclear power station. The heat exchanger in the tank is designed at 3% of the rated power. In the design process of PL-PRHRS, in order to compare with the SL-PRHRS which proposed in the present work, as shown in Fig.1 (a), it's assumed that the height difference between the heat source (reactor core) and heat sink (water tank) is the same with the SL-PRHRS, as well as the volume of water tank. What's more, to limit the trepanning on the primary pipe, there is only one loop of PRHRS in the design. The system structure is shown in the Fig.1 (b) and the design parameters are shown in the Tab. 1.

Table 1 System design parameters.

Parameters	Value
Height difference between SG and water tank	17.24m
Water tank volume	360m ³
PRHRS heat exchanger inner/outside diameter	19/22 mm
PRHRS heat exchange area	54.08m ²



(a) SL-PRHRS.



(b) PL-PRHRS.

Fig.1 Schematic diagram of PRHRS.

Figure 1(b) is the system schematic diagram of PL-PRHRS. The heat exchanger adopts a straight tube type internal cooling method, and the heat transfer tubes are arranged in a triangle shape to facilitate the turbulent flow of the shell side fluid. The inlet and outlet of the heat exchanger are connected with the hot and cold leg respectively. An isolation valve is located on the inlet pipe, which is always opened, and two isolation valves are located on the outlet pipe, which are always closed. Two isolation valves are located on the hot and cold leg to isolate the SGs if heat transfer tube break accident happens. There is one safety valve on the top to prevent the overpressure of the SGs.

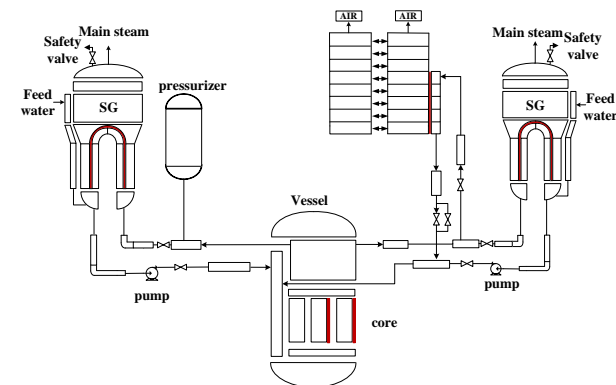
When the SBO or other accidents which could cause the heat transfer failure in SGs occur, such as LOCA, the passive or active isolation valve will be opened. But because of the stopping behavior of the primary pump, there is a delay in the establishment of natural circulation. When the pump stops, a natural circulation would be established between the reactor core and the PRHR heat exchanger.

With the operating of PRHRS, boiling will occur on the outer surface of the heat exchanger tube and if the steam can't be completely condensed in the water tank, it will be released into the containment which would cause the drop of the water level.

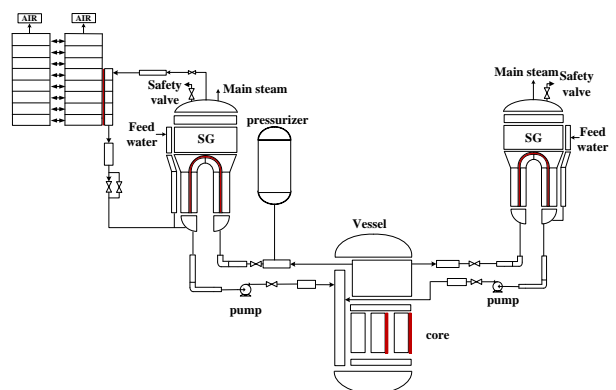
2.2 Thermo-hydraulic model description

The safety analysis software Relap5/MOD4.0 is used to model the reactor system and the PRHRS. The simplified node graphs of the SL- and PL-PRHRS are shown in Fig.2. As shown in Fig.2, the reactor physics is calculated using a point reactor dynamics model

during the modeling process. The core is divided into three parts: the bypass channel, the hot channel and the average channel to reflect the power distribution in it. In order to accurately simulate the large space natural circulation, nodes are divided by the proven method [5] to simulate the left part and the right part of the water tank, respectively.



(a) PL-PRHRS.



(b) SL-PRHRS.

Fig.2 Node graph of PRHR systems.

3. Results and discussion

In this section, the calculation results are shown and discussed. At first, the start-up transient characteristics analysis of the system comparing with the SL-PRHRS is presented and then the TPCLT is designed to promote the long-term characteristics of the system.

In the accident, such as SBO or LOFA, PL-PRHRS and SL-PRHRS are comparable because they have the same function. So the simulation of SBO is presented at first to compare the transient characteristics between the two types of PRHRS. The time sequence of SBO accident is showed in table 2.

Table 2 Time sequence of SBO

Time	Event	Trigger signal
50s	Coolant pumps start idling	SBO accident
50.8s	Reactor shutdown	Low coolant pump speed
51.0s	Main feedwater and turbine stop	0.2 s delay
55.0s	PRHRS starts	4 s delay

In the accident, the SG safety valve opens when the pressure is higher than their maximum operating pressure, 6.35Mpa. The thermal hydraulic parameters of the primary loop are shown in the Fig.3 to Fig.5.

Figure 3 shows that the power removed by the two PRHRSs is equal to the reactor decay power at the same time, while the beginning times are quite different from each other. This is because, when the primary pump trip, the stopping behavior of the pump would make the pressure large at the outlet of PL-PRHRS, which would stop the coolant flowing into the PRHRS.

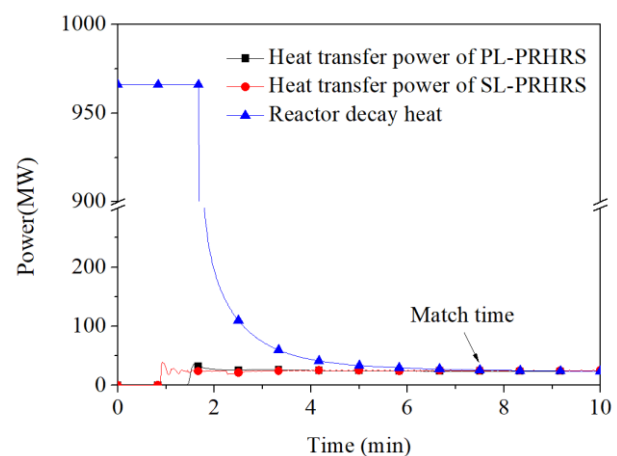


Fig.3. Variation of heat removal and reactor power .vs. time.

Another reason is that the established of natural circulation needs more power than the SL-PRHRS, because the distance between the core and the heat exchanger is long. Also for this reason, the temperature difference between the inlet and outlet of the core oscillates at the beginning and becomes larger with the operation of the system, as shown in Fig.4. On the other hand, with the stop of pump, the cool water in the PRHRS flows into the primary loop and makes the temperature of the coolant falling rapidly. Under the combined actions from above, for PL-PRHRS, the decreasing of the temperature is faster and the beginning time of heat transfer by PRHRS is later than

SL-PRHRS, as shown in Fig.4 and Fig.5 (a). For the same reason, the pressure of the pressurizer also drops faster, as shown in Fig.5 (b).

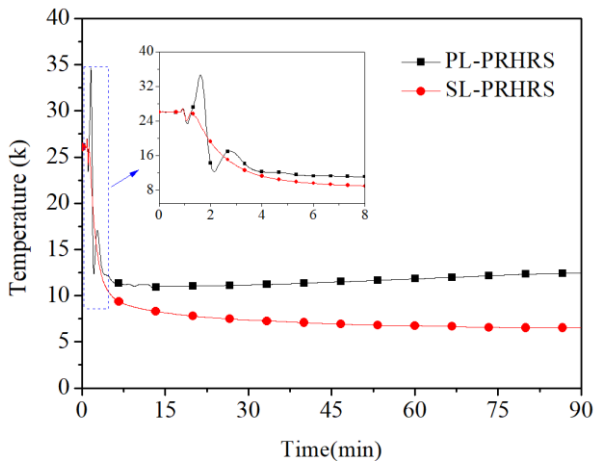
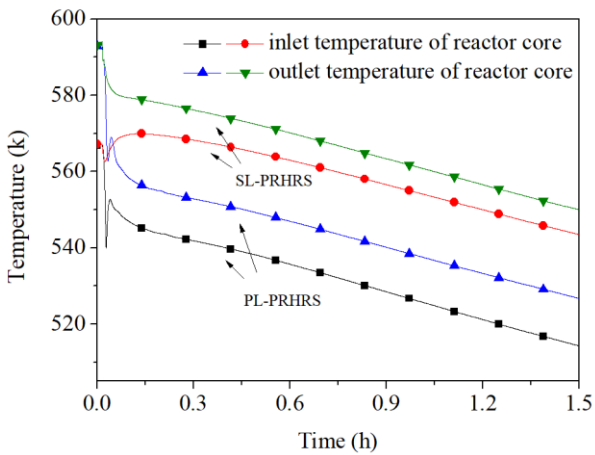
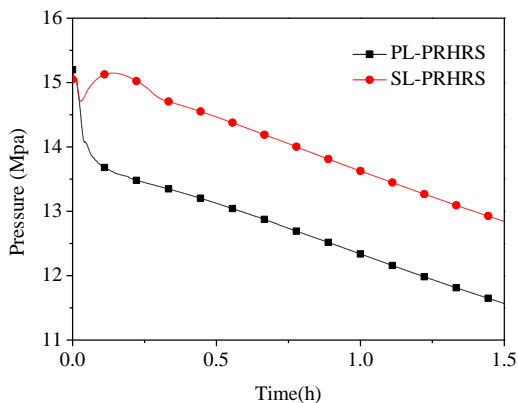


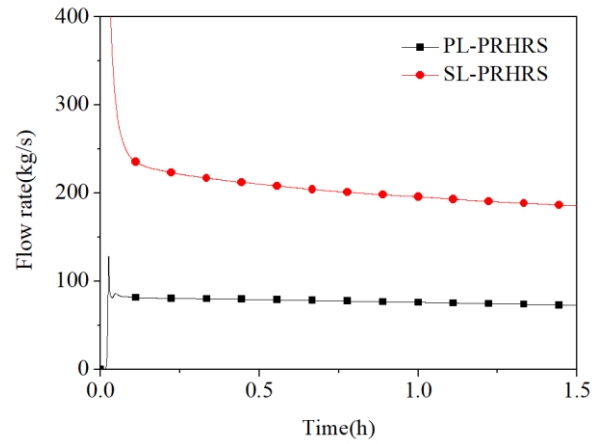
Fig.4 Variation of temperature difference between inlet and outlet of the core .vs. time.



(a) Temperature of the primary coolant.



(b) Pressure of the pressurizer.



(c) Flow rate of Natural circulation.

Fig.5 Variation of main parameters of primary loop .vs. time. Figure 5(c) presents the flow rate of the coolant natural circulation with time. The reason for the peak of the PL-PRHRS is that, the large temperature difference likes a switch to the start-up of natural circulation and overflow will happen when the switch is turn on, and then the flow rate will reduce to a stable value.

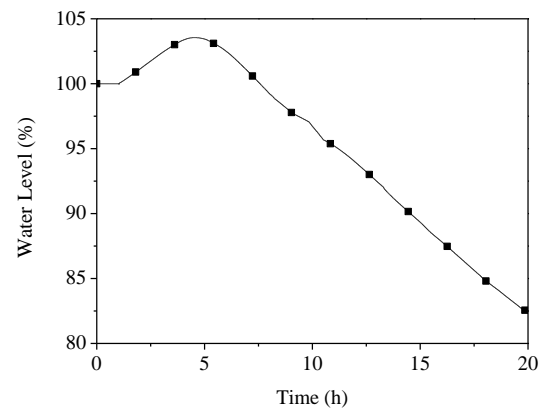


Fig.6 Variation of water level in the tank .vs. time.

Figure 6 shows the variation of water level in the tank during the long-term operation. Although, the system have the ability to remove decay heat for more than 20 hours, 15% of water volume has reduced because of the boiling in the tank, which means the availability of the PRHRS strongly depend on the initial water volume.

Take the atmosphere as the heat sink might be a good idea to reduce the volume of water tank and to ensure the effectiveness of other systems when the tank is shared, but the effect of medium loop with single phase is poor [4], so a TPCLT is designed as the medium loop between the tank and the atmosphere. The TPCLT is a kind of heat pipe which is designed based on the two-phase natural circulation and has the characteristics of

simple structure and high heat transfer efficiency. It's suitable for long distance heat transfer because of the separation of evaporator and condenser [6]. Therefore, the intermediate loop based on the TPCLT is designed and the system structure is shown in the Fig.7, and the design parameters are shown in Table 3.

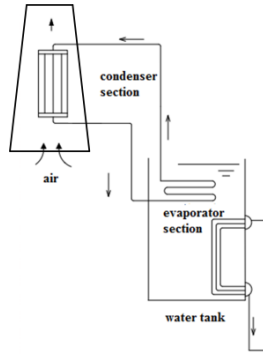


Fig.7 System structure of the TPCLT.

Table 3. PRHRS System design parameters

Parameter		Value
TPCLT	Material	304
	Working fluid	Water
Heat exchanger	Arrangement/number of tubes	aligned/63
	Outside/inside diameter/ length	25/21/800mm
Condenser	Length /included angle of fin	50mm/ $\pi/2$ rad
	Distance between tubes/ lines	30/10mm
	Length of the condenser diagonal	0.93 m

Because the operating pressure of TPCLT is always below the atmospheric pressure [7-8], the current models are not mature to simulate it accurately. The conjugate boundary method (CBM) is chosen to calculate the average temperature in the TPCLT. The implementation of the CBM is based on the following assumptions:

1. Assume that the operation of the TPCLT is a near-steady state process.

Since the heat transfer in the TPCLT is the phase change heat transfer with quite high efficiency, there is basically no hysteresis effect in the heat transfer inside the TPCLT and the operating state is considered to be near-steady state.

2. Assume that the saturation temperature of the working fluid can be used as the average temperature in the TPCLT.

Since there is almost no non-condensable gas in the system, it can be considered that the temperature differences of the different stations inside the TPCLT are so small, so that the saturation temperature of the working fluid can be used as the average temperature.

More discussion and verifications of the method have been presented in the present work [4].

According to the basic energy conservation process, the conjugate boundary equation under such boundary condition can be derived as:

$$M_1 C_{p1} \Delta T'_1 = K_1 A_1 \Delta T_1 \quad (1)$$

$$K_1 A_1 \Delta T_1 = K_2 A_2 \Delta T_2 \quad (2)$$

$$K_2 A_2 \Delta T_2 = M_2 C_{p2} \Delta T'_2 \quad (3)$$

Where, M_1, M_2 are respectively heated water flow and air flow, kg/m^3 ; C_{p1}, C_{p2} are the constant pressure specific volume of heated water and air, $\text{kJ}/(\text{kg} \cdot \text{K})$; $\Delta T'_1, \Delta T'_2$ are the inlet and outlet temperature difference between water and air, K ; K_1, K_2 are the heat transfer coefficient of evaporator and condenser, $\text{W}/(\text{m}^2 \cdot \text{K})$; A_1, A_2 are the heat exchange area of evaporator and condenser, m^2 ; $\Delta T_1, \Delta T_2$ are the heat transfer temperature difference of the evaporator and the condenser, K .

The models are coupled with Relap5 and the calculation time is 20 hours.

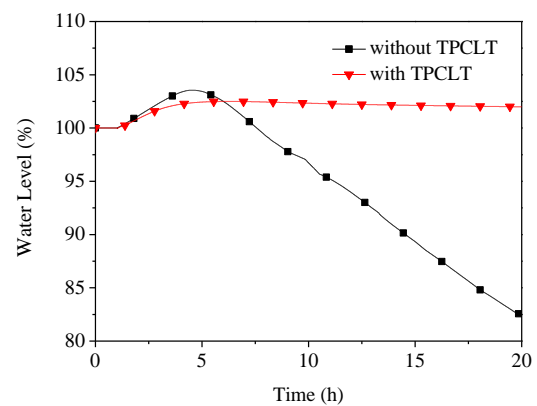


Fig.8 variation of water level in the tank .vs. time.

Figure 8 presents the comparison of water level between the PRHRS with and without TPCLT. From

the figure, the water level in the tank of the system with TPCLT has almost no decline which means the relationship between the PRHRS and the water volume is reduced considerably, and the safety system is more reliable.

4. Conclusion

A passive residual heat removal system based on the primary loop has been designed and simulated by the Relap5/MOD4.0 software. The results show that the PL-PRHRS can remove the decay heat effectively. Comparing with the SL-PRHRS, the temperature of the coolant of the system decrease faster and the decay heat removal process is established slower because of the pump stopping behavior and the high requirement of natural circulation power. To optimize the long-term performance of the PL-PRHRS and reduce its dependence on the initial water volume of water tank, a TPCLT is designed to transfer the heat to the atmosphere. The medium loop and air are simulated and coupled with Relap5/MOD4.0 by conjugate boundary method. The calculation shows that the optimized system reduces the dependence of PRHRS on the water volume so that the tank volume could be smaller, and higher inherent reliability would be achieved especially when the tank is shared by other safety systems.

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