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Research on capability of secondary passive residual decay heat removal system after Main Feedwater Line Break (MFLB) accident

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ABSTRACT

All advanced NPPs are required to improve safety strategy to cope with design extension condition (DEC) after Fukushima accident. One design improvements for HPR1000 is adoption of secondary Passive Residual Heat Removal System (PRS) to cope with station blackout accident together with loss of all feedwater, which can help to strengthen defense in depth capability and enrich DEC mitigation measures. To make the best use of PRS decay heat removal capability, investigation of PRS startup performance and decay heat removal capability after MFLB accident are investigated based on HPR1000 RELAP5 model. PRS startup response featured by pressure, mass flow rate and void fraction are investigated under three startup strategies. Strategy 3(backflow valve open strategy) is recommended due to minimum fluctuation during initiating stage, in which strategy steam isolation valve is normally open and backflow isolation valve is used to initiate PRS. Then Main Feedwater Line Break (MFLB) accident was simulated with the assumption of loss of auxiliary feedwater. Response characteristics in primary loop and PRS are investigated. After PRS being initiated after scram with 60 s delay, natural circulation in PRS will establish rapidly, and decay heat will be removed under natural circulation operation mode. No overall boiling occurred in primary circuit before isolation of affected SG. Secondary PRS is adequate to remove decay heat after DEC.

1. Introduction

Passive Residual Heat Removal System (PRS) featured by more simplified system configuration and higher reliability, which is an important part of the passive safety system for advanced nuclear reactors. In PRS of Hua-long Pressurized Reactor (HPR1000), heat exchanger placed in heat exchange tank is used to cool the steam generated by the secondary side of Steam Generator (SG), and the heat will be released to water in tank. After being cooled, the condensed water flow back to SG secondary side to cool primary coolant, and then become steam again to flow into the heat exchanger again, thus forming a two-phase natural circulation flow. The goal of this system is to remove core decay heat for long term after shutdown and keep the reactor under safety state.

Passive heat removal technology has been widely adopted in the second and third generation nuclear power plant. There are two kinds of design ideas for current existed passive residual heat removal system, one is to discharge decay heat through primary circuit directly, such as AP600/AP1000 (Schulz, 2006), and CAP series (Zheng et al., 2016) (China Advanced Pressurized Water Reactor, such as CAP1400 and C-AP1700). The other is to remove decay heat through SG, such as System-integrated Modular Advanced Reactor (SMART) in Korea (Min et al., 2014) and HPR1000. Many researches have been carried out for each design through scaling experiments and code simulations, such as RELAP5, CATHARE and so on.

As Generation-III PWR designed independently by China, its demonstration project was also under construction. To perform natural circulation experiments on secondary PRS, Emergency Secondary Passive Residual Heat Removal System Integral Test Facility (ESPRIT) (Zhao et al., 2015) (Sun et al., 2017) has been established in Nuclear Power Institute of China (NPIC) (Feng et al., 2015). No other experimental facility and data were published due to technical confidentiality. Besides the system performance experiments based on ESPRIT, corresponding simulation and validation have also been carried out. Validation of Relap5 code capability in simulating secondary PRS and two-phase natural circulation was also based on ESPRIT data.

In this paper, HPR1000 secondary passive heat removal system (PRS) model is established with RELAP5 code, which will be preliminary simulated with certain primary boundary conditions of SG. Then, appropriate startup strategy was adopted after comparing PRS response under three different strategies. Finally, Main Feedwater Line

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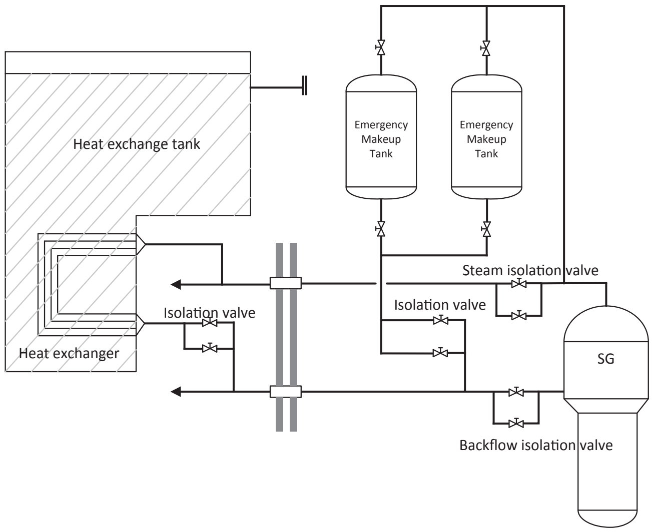

Fig. 1. Schematic diagram of secondary PRS.

Break accident (MFLB) was simulated based on integrated model of HPR1000 with PRS. Response of primary and secondary circuit featured by pressure, temperature, mass flow rate and heat transfer rate in PRS were investigated, especially after secondary PRS come into operation.

2. Description of HPR1000 secondary PRS and simulation

HPR1000 reactor coolant system consists of three loops connected in parallel to the reactor pressure vessel; each loop contains a secondary PRS in SG secondary side. Secondary PRS is designed to keep reactor safety passively for 72 h in case of loss of offsite and onsite power together with auxiliary feedwater system failure. Each secondary PRS is composed of secondary side of SG, heat exchange water tank, emergency heat exchanger, 2 emergency makeup tanks, corresponding pipeline and valves (Xing et al., 2016). The schematic diagram of PRS is shown in Fig. 1 (Fei YI, 2016). The residual heat exchanger is immersed in heat exchange water tank, the inlet of the heat exchanger is connected with the head of the SG, and the outlet of the heat exchanger is connected with SG main feedwater supply pipe. Secondary PRS is connected in parallel with the SG secondary side system. More descriptions of HPR1000 are available in (Sui et al., 2017).

Under normal operation, PRS and main system is isolated through isolation valve. After accident, electric control valve will open after failure, subcooled coolant in cold pipeline will flow into SG through main feedwater supply pipeline. Mainly isolation valves include steam isolation valve and backflow isolation valve; different valve operation logics can be adopted to start PRS according to different startup strategies. After being heated by primary coolant in SG, saturated steam will flow upwards and finally come into heat exchanger located in heat exchange tank to be condensed and flow back to secondary side of SG. Stable natural circulation will be established by the common driven force of gravity pressure difference and condensation suck force. Decay heat will be discharged into heat exchange water tank, and then be released to atmosphere through evaporation. Considering PRS steady-state initialization and integrated HPR1000 steady-state initialization could affect each other if in one integrated model, initializations of PRS and integrated HPR1000 are performed separately. In following PRS steady-state simulation, most primary model are isolated, boundary conditions are coolant mass flow rate and inlet temperature in SG primary side.

Nodalization of PRS with RELAP5 code is shown in Fig. 2. Component 350–639 represent ascending pipes, component 630 is representative heat transfer tube, component 617–980 represent descending pipes. Valve 386 and 623 are steam isolation valve and backflow isolation valve respectively. In PRS steady-state simulation, these two valves are all open. For representative heat transfer tube 630, heat structure 1630 are attached to perform heat transfer between coolant in PRS loop with water in heat exchange tank. Heat transfer boundary condition in heat exchange tank is simplified as constant temperature with temperature of 300 K. Heat transfer coefficient for ranges from 7910 W/(m^2.K) to 1200 W/(m^2.K) from inlet to outlet according to different temperature difference and mass flow rate difference.

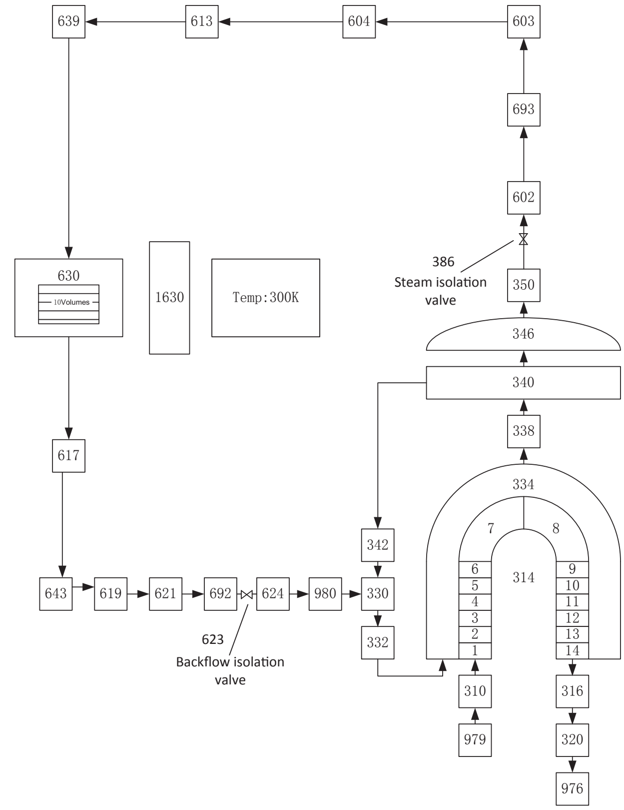

Fig. 2. Nodalization diagram of secondary PRS.

In the light of RELAP5 prediction is sensitive to the nodalization, the nodalization sensitivity analysis was carried out. Four different kinds of nodalization were tested, namely the Nodalization I, Nodalization II, Nodalization III and Nodalization IV. For Nodalization I, there are 80 nodes in total, 70 nodes in loop circuit and 10 nodes in heat exchanger, as shown in legend of Fig. 3. Other nodalization scheme can also be found in this legend. It can be found that mass flow rate simulation results for nodalization I and II are very close, which shows node number in loop circuit has little influence on natural circulation

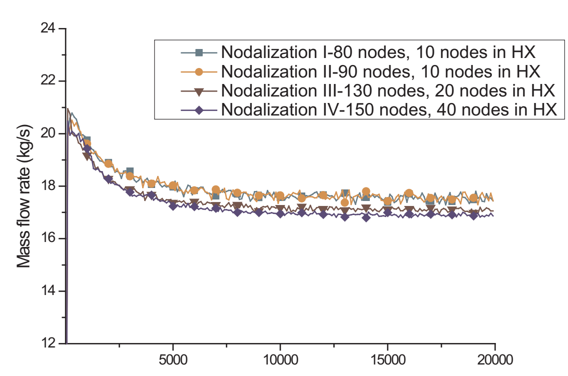

Fig. 3. Nodalization sensitivity analysis of PRS RELAP5 model.