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Accident analyses for china pressurizer reactor with an innovative conceptual design of passive residual heat removal system

Mingjun Wang, Dalin Zhang*, Suizheng Qiu, Wenxi Tian, Guanghui Su

State Key Laboratory of Multiphase Flow in Power Engineering, School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- An innovative passive system design concept was proposed.
- Remote trigger control was adopted in the new passive system.
- Transient characteristic of new PRHRS was studied during normal operation, SBO and FLB.
- New design type is successful.

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ABSTRACT

An innovative passive safety system design concept for CPR 1000 nuclear power plant (NPP), proposed based on the original passive residual heat removal system (PRHRS) design, is presented and studied in this paper. The new type PRHRS avoids use of trigger valve inside the containment and adds an external water tank as the trip of PRHRS operation. The new design concept can realize functions of system remote control and trigger, while the external water tank can provide emergency water for steam generator (SG) in case of loss of feed water accident. Also, the advantages to use a valve and a tank located externally to containment are including the more reliability in implementing valve in pipes at low pressure, possibility operating manually the valve to start the system, refilling the tank in case of long time cooling and maintaining the valve easily. Best-estimate transient simulation code Relap5/MOD3.4 is applied to study the behavior of new design PRHRS and transient characteristics of primary loop system during normal condition and accident conditions. The transient processes of Station Black-Out (SBO) and Feed-water Line Break (FLB) accidents are studied to verify the function of new design PRHRS. Results show that the effect of valve position change from inside to outside containment can be ignored for the new design PRHRS in normal operation and the external valve can trip the operation of PRHRS in case of accidents. The new design PRHRS can remove core residual heat from primary loop effectively through establishing the stable natural circulations in the primary loop and PRHRS loop when the SBO and FLB accidents occur. It also can supply the emergency water to the SG in the event of FLB accident and realize safe reactor shutdown. Results indicate that the new design concept PRHRS in this work is potential and successful in future application.

1. Introduction

The innovative safety systems often rely on passive safety measures like gravity injection or natural circulation and do not need external input energy to operate, improving inherent safety for Pressurized Water Reactor (PWR).

For China Pressurized Reactor (CPR1000), much research related to passive safety system has been performed in recent years. Zhang et al. (2011) has designed a type of secondary emergency passive residual heat removal system (PRHRS) for CPR1000 and studied the transient characteristics of the primary loop system and the PRHRS in the event of a feed line break (FLB) or loss of heat sink accident. Another type of secondary PRHRS has been designed and studied in the case of Station Black-Out (SBO) accident for CPR1000 by Wang et al. (2012). The results of the study demonstrated that the designed secondary PRHRS was effective and meaningful to CPR1000. In addition, experimental research on passive safety systems was carried out for CPR1000 NPP (Xiao et al., 2003), the results of which indicated that the passive system was effective and reliable in principle and could meet the design and safety requirement.

* Corresponding author.
E-mail address: dlzhang@mail.xjtu.edu.cn (D. Zhang).

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For above types of designs, the trigger valve is necessary to realize the passive system function. The trigger valve is closed and prevents the heat transfer by insulating the heat exchanger (HX) tubes with overheated steam during normal operation. If the trigger valve is opened, the steam is condensed in the passive safety HX and cold water flows from the HX to the SG. In this case, an effective natural circulation is established allowing passive removal of the decay heat. Preliminary calculations showed the use of a trigger valve brought significant system uncertainty and construction problems (Meloni and Pignatel, 1998; Meloni, 1998).

To overcome this problem, a new system configuration, which mainly consists of a HX pool, external pool and a heat exchanger, was proposed by ENEA and SIET (Achilli et al., 2002). The research on heat removal by in-pool immersed heat exchangers has been performed at SIET laboratories using the PERSEO facility by experimental method (Ferri et al., 2005). In addition, the best estimate code Relap5 was utilized as design instrument during all phases of this project. Results generally show a good agreement between experimental and calculated data and identify some code limits.

As discussed above, the design types for CPR1000 among different works always similarly contain a trigger valve in the pipe connected to the SG or reactor, increasing system uncertainty greatly. The assessment of the reliability of passive systems is a significant issue to be solved for their extensive use in future nuclear power plants (Zio and Pedroni, 2009). Therefore, in this study, based on the original type of SG secondary PRHRS, the new conceptual PRHRS which avoids the use of trigger valve connected to the SG is developed. An external water tank is added to the PRHRS. An external valve connects the external water tank and HX tank filled with air initially. Furthermore, the model of the primary loop and the PRHRS were established using Relap5/MOD3.4 (2001a,b) to investigate the core residual heat removal capability of the new concept PRHRS. To investigate the function of PRHRS, the transient accidents, leading to the loss of secondary side feed water and short of SG water volume, are selected to study. In this work, the Station Black-Out (SBO) and Feed water Line Break (FLB) accidents were simulated.

2. New PRHRS conceptual design

The new concept PRHRS, which adds an external water tank as the heat sink and trip of PRHRS operation, is also connected to the SG secondary side and consists of three independent loops. The original design schematic diagram and new PRHRS design diagram are shown in Fig. 1. Compared with the original design, the great difference is that the valve is avoided inside the containment in the new design, increasing the reliability of PRHRS significantly. In the original PRHRS type, the trigger valve connects the HX with SG, controlling the start of PRHRS. The steam in the SG flows to HX through ascending pipe and is condensed in the HX. At last, the condensed coolant flows back to SG through the descending pipe. The heat is transferred to the water in the water tank, taking the primary loop heat out. For the new type PRHRS, there are two tanks, which are HX tank and external water tank. The HX tank is full of air in the normal condition and the external valve will trip the operation of the PRHRS, in which case the HX is filled up and the heat transfer begins. Furthermore, the external water tank can provide the emergency water to SG in case of loss of feed water accident. So the start valve is tripped based on the accident signals. The feed water valve is tripped when the SG needs to be supplied water.

Each new PRHRS loop is composed of a steam generator, an HX, an HX tank and an external water tank. Based on the power of CPR1000 NPP and capacity of each new PRHRS, the main parameters of new designed PRHRS are shown in Table 1.

Table 1
Main parameters of the new PRHRS.

Parameters	Values
Area of ascending pipe	0.04917 m^2
HX area	300 m^2
Area of descending pipe	0.00836 m^2
Area of HX tank	10 m^2
Height of HX tank	12 m
Volume of HX tank	98.88 m^3
Area of external water tank	113.04 m^2
Height of external water tank	12 m
Flow area of valve between two tanks	0.1256 m^2
HX active length	3.0 m
Flow area of valve between external water tank and SG	0.005 m^2

3. Relap5 modeling

The best-estimate transient simulation code Relap5/Mod3.4 is utilized to carry out the calculations presented here. Only one of the three loops and corresponding PRHRS Relap5 node is shown due to the system symmetry. The reactor vessel, reactor core, pressurizer, reactor coolant pump, accumulators and steam generators are modeled in detail. Other important auxiliary systems are modeled using time-dependent volume (TMDPVOL) and time-dependent junction (TMDPJUN) in this study.

As shown in Fig. 2, for the PRHRS, the HX, saturated steam ascending pipe, condensed water descending pipe, HX tank, external water tank and corresponding pipes and valves are simulated detailedly by different Relap5 models. The HX tubes heat transfer is modeled by heat structure. The external isolation valve trip is the switch for controlling PRHRS operation.

4. Results and discussions

The characteristics of the new PRHRS and CPR1000 NPP primary loop are studied in normal operational conditions and accident conditions in this section.

4.1. Steady analysis and PRHRS characteristic in normal operation

The steady state analysis is studied firstly for evaluating the CPR1000 Relap5 model and the effects of new PRHRS without valve. The main parameters comparison between Relap5 code steady calculation results incorporating new PRHRS design and CPR1000 design data under normal operational condition are shown in Table 2.It can be seen from comparison results in Table 2 that the Relap5 calculation values of important reactor thermal hydraulic parameters, i.e. primary pressure, primary loop flow rate, SG secondary side pressure, cold leg temperature and hot leg temperature, are in good agreement with the design values. The errors are all in the acceptable range. Therefore, the new PRHRS has almost no effect on the CPR1000 NPP in normal operation condition without valve used inside the containment. Based on the steady calculation model, the CPR1000 transient analysis and the function characteristic of new PRHRS are studied in the following sections.

Table 2
Steady calculation results comparison with design value.

Parameters	Value in this work	Design value	Error
Primary loop pressure (MPa)	15.709	15.500	1.35%
Reactor outlet temperature (°C)	329.852	329.800	0.016%
Reactor inlet temperature (°C)	293.858	292.400	0.5%
Thermal design flow rate (kg/s)	4661.273	4706.560	1.0%
SG pressure (MPa)	6.908	6.890	0.3%