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Development of the analysis tool for the water cooling type passive residual heat removal system of Chinese pressurized reactor

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ABSTRACT

An innovative design for Chinese pressurized reactor is the steam generator (SG) secondary side water cooling passive residual heat removal system (PRHRS). The new design is expected to improve reliability and safety of the Chinese pressurized reactor during the event of feed line break or station blackout (SBO) accident. The new system is comprised of a SG, a cooling water pool, a heat exchanger (HX), an emergency makeup tank (EMT) and corresponding valves and pipes. In order to evaluate the reliability of the water cooling PRHRS, an analysis tool was developed based on the drift flux mixture flow model. The preliminary validation of the analysis tool was made by comparing to the experimental data of ESPRIT facility. Calculation results under both high pressure condition and low pressure condition fitted the experimental data remarkably well. A hypothetical SBO accident was studied by taking the residual power table under SBO accident as the input condition of the analysis tool. The calculation results showed that the EMT could supply the water to the SG shell side successfully during SBO accident. The residual power could be taken away successfully by the two-phase natural circulation established in the water cooling PRHRS loop. Results indicate the analysis tool can be used to study the steady and transient operating characteristics of the water cooling PRHRS during some accidents of the Chinese pressurized reactor. The present work has very important realistic significance to the engineering design and assessment of the water cooling PRHRS for Chinese NPPs.

1. Introduction

The design of passive safety system was proposed to improve the safety and reliability of reactor, and the characteristics of PRHRS were studied by many researchers (HUANGYan-Ping et al., 2004; Wang et al., 2011; Xi et al., 2015). The operation principle of the safety system is based on the passive safety measures, such as the gravity or natural circulation caused by the density difference based on the existing pressurized water reactor (PWR) technology. The passive safety system could take away the residual heat of the core without any external power under the accident condition. The system can improve inherent safety for the PWR (Munther et al., 1996).

Chinese pressurized reactor is an advanced, safe, mature, and economical nuclear reactor which is a three-loop 1000 MWe pressurized water reactor. The major parameters of Chinese pressurized reactor are listed in Table 1(Zhang et al., 2011). Wang et al. (2014a) has studied the core degradation and the debris behavior during the Chinese pressurized reactor severe accident caused by SBO. In his study, the passive safety system was not concerned and the core degradation happened. If the passive safety system could operate during the SBO accident and the residual heat could be taken away, the core would not degrade. The passive safety system consists of the passive residual heat removal system, the passive containment cooling system, and the passive core cooling system. The passive safety system is common in the reactors of generation III, but is not commonly found in the reactors of generation II or II+. Hence, the passive safety system is suggested to improve the inherent safety of the Chinese pressurized reactor.

There are two kinds of the steam generator secondary side passive residual heat removal system: the air cooling type and the water cooling type. For the air cooling type, the coolant in the shell side of heat exchanger is air, and the residual heat is taken away by the natural circulation established between the HX and the environment through the air cooling tower. Zejun et al. (2003) has carried out the experimental research on air cooling type PRHRS for

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Chinese pressurized reactor. The results indicated that the passive residual heat removal system was effective and reliable in principle and could meet the design and safety requirement. Then Xiao et al. (2006) developed a thermal-hydraulic code on PRHRS and validate the code based on the experimental data. Zhang et al. (2011) has studied the air cooling type PRHRS for Chinese pressurized reactor. 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 were studied using RELAP5/MOD3.4. In addition, Xinian et al. (2001) developed a code SGSPRHR based on drift flux mixture flow model, and use it to analyze the transient characteristics of the air cooling type PRHRS in the event of the station blackout accident. For the water cooling type, the coolant in the shell side of heat exchanger is water, and the residual heat is taken away by water evaporation in the water pool. Zhang et al. (2012) has also studied water cooling type PRHRS for Chinese pressurized reactor by using RELAP5/MOD3.4. Another water cooling type of secondary PRHRS has been designed and studied in the case of Station Blackout accident for Chinese pressurized reactor by Wang et al. (2012). The emergency makeup tank was not concerned in Wang's design. Then Wang et al. (2014b) proposed an innovative conceptual design of water cooling type PRHRS, and studied the transient characteristics of the PRHRS in the event of the station blackout accident and feed line break accident using the RELAP5/MOD3.4. Wu et al. (2012) has developed an analysis software for a passive residual heat removal system, but it is only suitable for the once-through steam generator.

As discussed above, the design of air cooling PRHRS is investigated by using the best estimated code RELAP5, experimental method and independently developed code. However, the analysis of the design of water cooling PRHRS mainly depends on RELAP5, and little experiments and independently developed code can be referred. 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). Hence more analytical methods are needed to assessed the reliability of water cooling type PRHRS. SGSPRHR code is developed for the air cooling type PRHRS, so it is not suitable for the transient analysis of water cooling type. To meet the domestic demand of software autonomous scheduling and the design and safety requirement, an analysis tool for water cooling type PRHRS is needed to develop to study the transient characteristics of water cooling type PRHRS during the event of loss of heat sink or a station blackout accident. Therefore, in this study, an analysis tool is developed for the water cooling type PRHRS of Chinese pressurized reactor based on the drift flux mixture flow model. The preliminary validation of the analysis tool is made by comparing to the experiment data of ESPRIT facility. Then the analysis tool is applied to the water cooling type PRHRS of Chinese pressurized reactor and the transient characteristics of water cooling type PRHRS during the event of a station blackout accident are calculated by the analysis tool.

Table 1
Major parameters of Chinese pressurized reactor.

Reactor type	3-loop PWR
Core power	2895 MW (thermal)
Operating pressure	15.5 MPa
Fuel assembly	17 × 17 type
Core height	3.66 m
Design volume flow flux	22,840 m^3/h
Core inlet temperature	292.4 °C
Core outlet temperature	327.6 °C
Primary pump	Non-seal centrifugal pump
Steam generator	U-tube natural circulation

2. System description

The water cooling type PRHRS diagram is shown in Fig. 1. It is comprised of a SG, a cooling water pool, a heat exchanger (HX), an emergency makeup tank (EMT) and corresponding valves and pipes. There are two loops in the PRHRS, (a) steam water loop including steam generator, heat exchanger, and emergency feed water tank; and (b) water pool loop. When feed line break event or station blackout accident occurs, the increase of the steam generator secondary pressure leads the PRHRS to be put into operation. In the meantime, the emergency feed water tank isolation valve opens and the feed water is injected into steam generator by gravity. After absorbing the heat in the steam generator, the feed water evaporates and flows into the heat exchanger through the steam line. The steam is cooled in the heat exchanger and condensed to water, which flows back to the steam generator due to the influence of gravity. The natural circulation establishes gradually in the steam water loop. The coolant near the heat exchanger in the water pool starts to be heated and evaporates after the temperature reaches the saturation temperature. Hence, the residual heat transferred to steam generator is dumped to the environment.

3. Mathematical model and numerical method

The analysis tool is developed based on the drift flux mixture flow model under the following assumptions, (a) one-dimensional flow approach and (b) thermodynamic equilibrium between the two phases (water and vapor) existing in every control volume.

3.1. Basic mathematical model

As the flow and heat transfer of single phase exist in the water cooling PRHRS, the three fundamental conservation principles for single-phase flow are needed to describe this process. The equations are as follows:

Equation of continuity,

$$\frac{\partial \rho}{\partial \tau}+\frac{1}{A}\frac{dW}{dz}=0 \qquad (1)$$

where ρ is the density, kg/m^3. τ is the calculation time, s. A is the

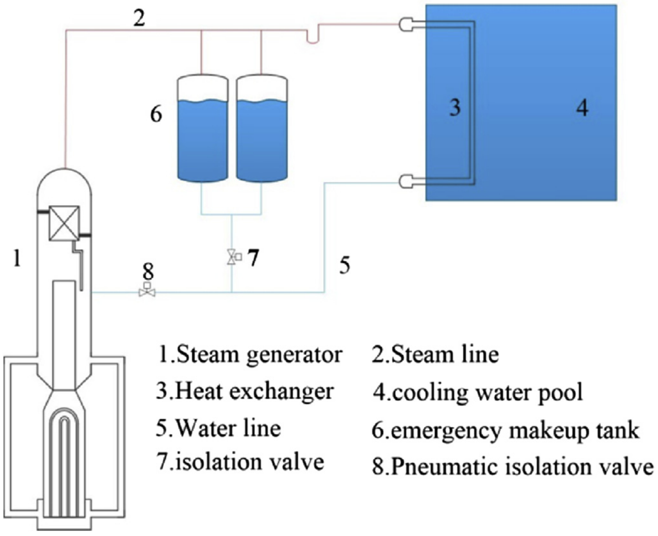

Fig. 1. Diagram of water cooling type PRHRS.