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Design and analysis of a new passive residual heat removal system

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HIGHLIGHTS

- An air cooling passive residual heat removal System (PRHRs) is designed.
- Using RELAP5/MOD3.4 code to analyze the operation characteristics of the PRHRs.
- Noncondensable gas is used to simulate the hydrodynamic behavior in the air cooling tower.
- The natural circulations could respectively establish in the primary circuit and the PRHRs circuit.
- The PRHRs could remove the residual heat effectively.

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ABSTRACT

The inherent safety functions will mitigate the consequences of the accidents, and it can be accomplished through the passive safety systems which employed in the typical pressurized water reactor (PWR). In this paper, a new passive residual heat removal system (PRHRS) is designed for a typical nuclear power plant. PRHRS consists of a steam generator (SG), a cooling tank with two groups of cooling pipes, an air-cooling heat exchanger (AHX), an air-cooling tower, corresponding pipes and valves. The cooling tank which works as an intermediate buffer device is used to transfer the core decay heat to the AHX, and then the core decay heat will be removed to the atmosphere finally. The RELAP5/MOD3.4 code is used to analyze the operation characteristics of PRHRS and the primary loop system. It shows PRHRS could remove the decay heat from the primary loop effectively, and the natural circulations can be established in the primary circuit and the PRHRS circuit respectively. Furthermore, the sensitivity study has also been done to research the effect of various factors on the heat removal capacity.

1. Introduction

Residual heat removal of the nuclear power reactor is an important part to the safety of nuclear power plant. In typical nuclear power plants, active residual heat removal system which is designed to fulfill the safety function needs reliable emergency power supply. If residual heat can be removed by natural circulation, such system can possess inherent safety features, i.e. the heat is eliminated to the environment by natural force (Xinian et al., 2001; IAEA, 2009). The application of passive safety systems (i.e. those whose operation takes advantage of natural forces such as convection and gravity) can be useful to the simplification of new nuclear power plant designs, and it also can eliminate the cost on the installation, maintenance and operation of active systems which require multiple pumps with independent and redundant electric power supplies.

The passive safety system has been extensively adopted by advanced light water reactors (ALWRs), e.g. AP1000, APR1400, EPR, CPR1000, etc. (Zhang et al., 2011; Yonezo Tujikura, 2000). In AP1000 nuclear power plant, passive safety systems that depend on gravity, compressed gas, natural circulation and evaporation are used to provide for long time cooling in the accidents while PRHRS could remove the residual heat of the core under an accident condition. The PRHRS of the WWER-1000 consists of four independent trains which connected to the respective loop of the steam generator (Juhn et al., 2000). Krepper and Beyer (2010) investigated the natural circulation phenomena in a passive decay heat removal system in large pools for BWR-1000 and ESBWR experimentally and numerically. Zio et al. (2010) estimated the safety margins of the PRHRS of the high temperature reactor-pebble modular (HTR-PM). The calculation results indicated that the PRHRS could remove the decay heat of the core effectively.

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In this paper, PRHRS which is connected to the steam generator shell side consists of four natural circulation loops. There is a cooling tank working as an intermediate buffer device to remove the decay heat to the AHX. Through the AHX, the core decay heat can be removed to the atmosphere finally. Based on the natural circulation characteristics, the arrangement form of the system and the size of equipment are determined. The RELAP5/MOD3.4 code was used to analyze the operation characteristics of the PRHRS and of the primary loop system when station black out accident occurs. In addition, the sensitivity study of heat removal capacity on main parameters has also been done.

2. System description

At the early stage of the accident, the residual heat is relatively large and should be removed by condensing the steam with the cold water in the water tank to achieve a rapid cooling of the system. However, at the late stage of the accident, the residual heat is small and air cooling is required to meet the demand of long-term cooling of the reactor.

Linked to the SG shell side, PRHRS removes the decay heat to the atmosphere through the natural circulation in both the primary and PRHRS loops. Since there are two loops in the reactor, the PRHRS contains two trains to match the primary loops. Each train of the PRHRS is composed of a steam generator (SG), an emergency cooling water tank with a group of C-type cooling pipes immersed in bottom and cooling coil furnished in the upper part, an air-cooling heat exchanger (AHX), an air-cooling tower, and corresponding pipes and valves for air cooling condition.

As shown in Fig. 1, the cooling water tank is placed in the containment which is a little higher than the steam generator and a group of C-type cooling pipes are immersed in the tank. The inlet of the C-type cooling pipes are connected to the main steam pipe as a tilt angle along the connecting pipe to insure that the steam or condensation water can flow from the steam generator outlet to the inlet of the heat exchanger smoothly. These connecting pipes and C-type cooling pipes are filled with water to prevent the steam from flowing into the PRHRS in normal condition. they supply water to the secondary side of the SG and maintain the water level when the PRHRS starts to work. The outlet of C-type cooling pipes is connected to the sewage outfall of the steam generator with normally-closed active and passive valves. There is a header in both the inlet and outlet of C-type cooling pipes. A group of cooling coils are arranged in the upper part of the cooling water tank, so the coil and AHX form another natural circulation circuit which full of pure water to remove the residual heat to the ultimate heat sink. Through the natural circulation in the air cooling circuit, the cooling tank works as an intermediate buffer device to ensure the rapid cooling in the early stage of the accident and long-term cooling in the late stage of the accident. To balance the volume change caused by the temperature change in the circuit, an expansion tank filled with nitrogen gas is placed in the highest point of this circuit. In order to cooling the air and/or discharged steam in the containment, air cooling pipes are installed inside the containment wall and connected to the air cooling natural circulation lines.

When station black out accident occurs, the protection system shuts down the reactor and the turbine trips. The pressure and water level of SG decrease which result in the closure of turbine, and feed water valve and the isolation valves of the PRHRS open at the same time. Then water flows into the secondary side of the SG to maintain the water level. Water in the SG can absorb the residual heat of the primary loop to evaporate into steam, and then rises and passes into the C-type cooling pipes immersed in the cooling water tank, where it is cooled and condensed to water, and flows back into the steam generator by gravity. Simultaneously, the heat is transferred to the water in the cooling water tank, and then to the atmosphere through the AHX finally. During the PRHRS operation, the single-phase natural circulation in the primary loop is established to transfer the core decay heat to the secondary side of the SG, and the other 3 natural circulations in the PRHRS loop are established to transfer the residual heat to the air.

3. System design

3.1. Major System parameters

The major parameters of the reactor are listed in Table 1, which base on the parameters of Qinshan phase 1 nuclear power station. This scheme adopted 3% of the rated power to design the passive residual heat removal system. The calculation model is established on the basis of conservation equations and the single-phase/two-phase natural circulation characteristics with basic assumptions,

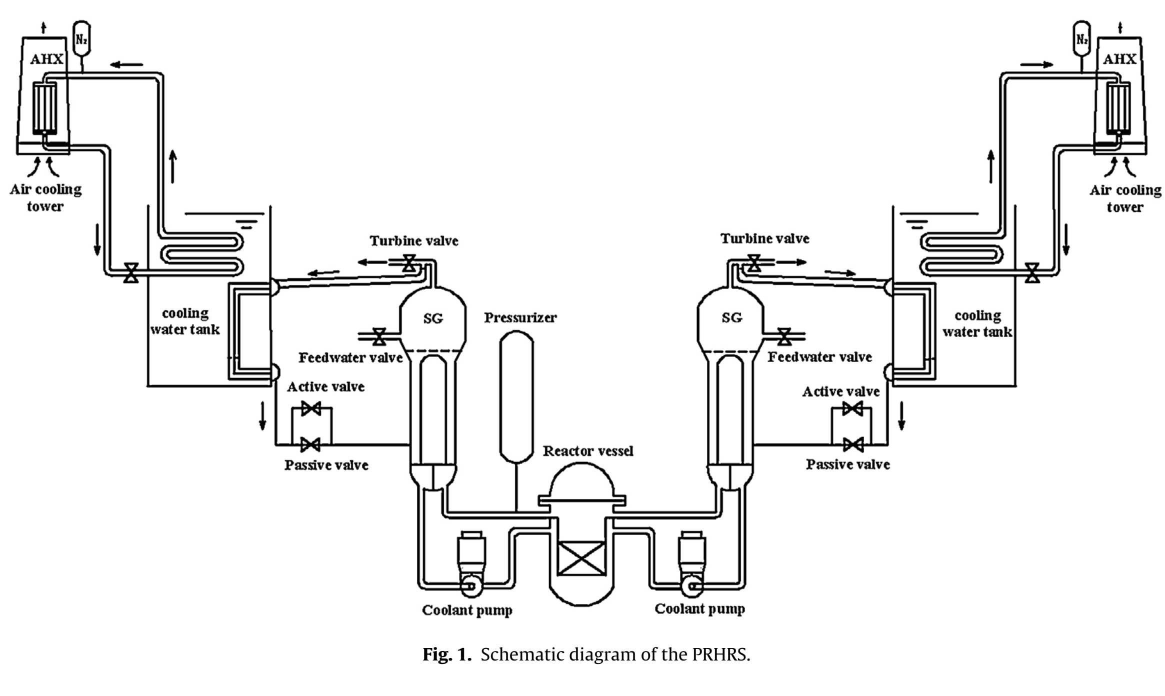

Fig. 1. Schematic diagram of the PRHRS.