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Operation characteristics analyses on a marine-type passive residual heat removal system

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ABSTRACT

A marine passive residual heat removal system can not adopt a huge water tank like that of AP1000 design due to the limited space. Considering the characteristics of marine nuclear power plants, a new type of passive residual heat removal system was applied to enhance the inherent safety features. The new passive residual heat removal system consists of a small-size intermediate water tank, an air-cooling tower and corresponding pipes and valves. The design capacity was evaluated based on the system safety and cooling rate. As a step forward, thermal-hydraulic analysis codes have been developed based on RELAP5. An additional force model and refined volume coordinate solver model were added. The results conclude that the reasonable passive residual heat removal system design capacity is 1.7% full power for IPWR200. The ocean motions make obvious effects on passive residual heat removal system operation characteristics, which should be considered during the design and operation to ensure sufficient safety margin. Besides, the passive residual heat removal system has been proved to be trustworthy and effective under typical ocean conditions based on the simulation results.

1. Introduction

In recent years, great efforts have been devoted to ensure the inherent safety of nuclear power plants, especially after Fukushima Daiichi nuclear accident. Reliability and efficiency of the residual heat removal after station blackout accident have become a great concern for nuclear safety. To be guaranteed, the passive safety systems relied on the gravity and natural circulation have been widely used in nuclear power plants, since they are independent of the auxiliary power or diesel power generators (Ayhan and Sokmen, 2016). Besides, the passive safety systems can also simplify safety systems and reduce the failure possibility caused by human interventions. In the AP1000 design, a heat exchanger (PRHR-HX) is placed in an in-containment refueling water storage tank (IRWST) to remove the decay heat by natural circulation and it can keep removing the residual heat for 72 h under non-LOCA accidents (Schulz, 2006). The PRHR-HX in VVER removes the decay heat by cooling the steam in the secondary loop with the heat transferred to the outside air under design basis accidents (DBAs) and beyond DBAs (Ayhan and Sokmen, 2016). Krepper and Beyer (2010) investigated the natural circulation phenomena in large pools of passive systems for BWR-1000 and ESBWR. The natural circulation transient characteristics of primary loop and PRHR loop in IPWR200 were studied to investigate the residual heat removal capability of the PRHR system (Xia et al., 2014). In general, numerous studies have been done on analyzing the characteristics of PRHR systems, which lead to mature and wide PRHR system use in the commercial reactors.

For the nuclear submarine and ship, redundant auxiliary systems are placed in the cabin to assure the reactor safety all the time since they are always far from support and are not available to the mobile power systems like mobile electric generators. Nonetheless, the redundant auxiliary systems will occupy the limited space that can be used for crew or other equipment. The passive safety systems are being introduced to replace the active ones to save equipment and space. However, the operational characteristics and reliabilities of the passive safety systems of the marine nuclear power plants are significantly different from those of the land-based reactors because of the ocean movements. Ocean movements can change the driving force made by gravity and density difference, and add additional forces caused by various accelerations, and all of the above are crucial to the reactor safety and have not been fully studied.

Due to the effects of ocean waves, the coolant flow and heat transfer characteristics of floating reactor are different from that of land-based stations, which attracts lots of attentions (Yan, 2017). Ishida and Yoritsune (2002) analyzed the effects of

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Nomenclature

Acronyms

ACL	Air-Cooling Loop
AHX	Air-cooling Heat Exchanger
BWR	Boiling Water Reactor
CMT	Core Makeup Tank
DBA	Design Basis Accident
DRACS	Direct Reactor Auxiliary Cooling System
DRX	Deep-sea Reactor X
ESBWR	Economic Simplified Boiling Water Reactor
HX	Heat Exchanger
IPWR	Integrated Pressurized Water Reactor
IRWST	In-containment Refueling Water Storage Tank
LOCA	Loss of Coolant Accidents
MFIV	Main Feed Water Isolation Valve
MSIV	Main Steam Isolation Valve
NPP	Nuclear Power Plant
OFNP	Offshore Floating Nuclear Plant
OTSG	Once Through Steam Generator
PRHR	Passive Residual Heat Removal
RELAP	Reactor Excursion and Leak Analysis Program
RPV	Reactor Pressure Vessel
SBO	Station blackout
TDV	Time Dependent Volume
VVER	Water-Water Energetic Reactor

heeling or heaving motions on the thermal-hydraulic behavior of the deep-sea research reactor DRX by using RETRAN02 code. Murata et al. (2002) carried out series of experiments on single-phase natural circulation and discussed the phenomenon of composite superposition pulse caused by self-oscillation and fluctuation conditions. Hao et al. (2012) developed a computational code for marine nuclear power plants to model the natural circulation behaviors and studied the effects of ocean motions. A variety of single-phase natural circulation experiments have been also carried out by Tan et al. (2009) to study flow and heat transfer behaviors under rolling motion. Yan et al. (2010) developed the flow and heat transfer models for single-phase flow in rolling motion and the correlations of fractional resistance and heat transfer coefficients were obtained based on his work. However, most of the existing studies concentrated on simple experiment loops, the localized heat transfer or flow resistance characteristics under the ocean conditions, or the natural circulation in the primary loop. Few investigations focused on the effects of ocean conditions on the operational characteristics of PRHR systems, which are critical for the safety of marine nuclear reactors.

In this paper, a new type passive decay heat removal system was adopted to enhance the reactor safety. Heat exchanger design parameters of different design capabilities have been determined based on the design calculations. The optimized PRHRs capacity should take both the system safety and the coolant cooling capability into consideration. In addition, thermal-hydraulics codes have been developed based on RELAP5. The relevant physical models have been added to calculate the additional pressure drop introduced by ocean motions. The effects of ocean conditions on the system operational characteristics were studied.

2. System description

The Integral-type Pressurized Water Reactor (IPWR200) is a small modular reactor designed for ship propulsion with 220 MW (100% FP) (Khan et al., 2013). Plate-type fuel assemblies were used to achieve a compact core arrangement. Besides, twelve once-through steam generators (OTSGs) are housed around the core, and each group (three OTSGs) is connected with a main pump. Other details of IPWR200 design can be found in the references (Xia et al., 2014). The key parameters of IPWR200 are listed in Table 1.

The passive residual heat removal system (PRHR) has been applied for IPWR200. Various PRHR design concepts have been proposed in the existing reactors. For AP1000, primary coolant flows into the PRHR-HX and transfers the heat to the heat sink IRWST, and flows back to the core in the following via the steam generator (Schulz, 2006). Finally, the decay heat is transferred to the low-temperature water in the IRWST. Therefore, a huge water tank and sufficient height difference are needed. However, for the marine reactor, the space is extremely limited, whether it is submarine or aircraft carrier. The design of VVERs employed an air cooling tower as an ultimate heat sink instead of the IRWST in their PRHR system. However, the air cooling tower will occupy too much space due to the small heat transfer coefficient at the air side. Besides, the heat removal capacity is extreme low at the startup stage of this PRHR system, which will result in high pressure and temperature in the primary loop in a short period of time (Xiao et al., 2003; Zhuo et al., 2014). In current OFNP design, Zhang et al. (2016) combined the functions of core makeup and heat removal together by placing a heat exchanger in the CMT to transfer decay heat of the reactor to the seawater via a DRACS outside the containment. However, this kind of PRHR system needs an intermediate loop below the water surface, which means additional waterline in the ship. Besides, connection between the CMT lines and reactor vessel will increase the risk of LOCA. The above-mentioned three PRHR systems are not suitable for the marine application due to space limitation and safety requirement. In the current work, PRHR system proposed by Lv et al. (2016) was employed as the prototype to remove the decay heat of IPWR200. The capacity of the PRHR system was re-designed and discussed to meet the requirement of safety.

Table 1
Major parameters of IPWR200.

System parameters	Values
Initial core power	220.0 MW
Fuel type	Plate type
Number of fuel assemblies	109
Pressurizer pressure	15.5 MPa
Core inlet temperature	562.15 K
Core outlet temperature	594.15 K
Primary coolant flow rates	1200.0 kg/s
Main steam flow rates	88.0 kg/s
Main steam pressure	3.0 MPa
Main feedwater temperature	373.15 K
Main feedwater pressure	4.5 MPa

The PRHR system consists of two loops, the intermediate loop and air-cooling loop (ACL), which are made up by a water tank, an air-cooling tower. The residual heat is transferred through two sets of heat exchangers in the water tank, as shown in Fig. 1. The C-type heat transfer tubes are immersed at the bottom part of the water tank and connected to the steam generator outlet. A set of cooling coils is furnished in the upper part of the water tank. The decay heat is ultimately released to the atmosphere via the air-cooling heat exchanger (AHX) in the air-cooling tower. Finned pipes are adopted in air cooling heat exchanger, which can improve the heat transfer efficiency to a great extent. The inlet of the PRHR system is connected to the main steam pipe, while the outlet is