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Preliminary Investigation of Pressure Effect of the Emergency Cooldown Tank on Accident Grace Period of Small Modular Reactors

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1. Introduction

Small modular reactors (SMRs) are considered attractive for developing countries due to its relatively low capital cost and additional functions such as desalination, district heating. In addition, passive safety concept is embodied to most of the safety systems to ensure sufficient grace period without any response.

A passive residual heat removal system (PRHRS) is a critical passive safety system to prevent overheating and degradation of the core. The PRHRS loop connects the steam generators (SGs) and the emergency cooldown tanks (ECTs). Upon hypothesized accident scenario, decay heat is transferred from the core to the SGs, where the transferred heat is designed to be removed in the ECTs by natural circulation. The PRHRS is adopted for integral pressurized water reactor (IPWR) type reactors such as SMART and IRIS. Bae et al. confirmed the PRHRS for SMART had capability to remove the decay heat during accidents such as MSLB, SBLOCA, and TLOF [1].

Because the PRHRS utilizes the water inside the ECT as a coolant, its heat removal performance is affected by thermal-hydraulic characteristic of water. If the heat exchanger in the ECT is exposed to air due to decreased water level inside the ECT, the heat removal efficiency is deteriorated. Na et al. showed that the coolant temperature increases if the water level becomes lower than the height of the heat exchanger [2]. This implies that the water level of the ECT is a critical parameter in determining the safety performance of the ECT.

Focusing on the ECT performance only, two strategies can be suggested to mitigate the water vaporization inside the ECT. Firstly, if some portion of heat transferred to the ECT is removed, the time of the water vaporization can be delayed. The other strategy is to keep the generated vapor inside the ECT by designing it into a closed system. Recently, Na et al. reported successful reduction of water vaporization using the dry air-cooling tower (DACT). However, making the ECT as a closed system could result in pressurization of the ECT due to heat expansion and boiling of water. Pressurization of the ECT increases the boiling point of water while the heat of vaporization decreases as shown in Fig. 1. Because the total heat removed by the PRHRS is expected as the sum of sensible heat and latent heat of water, the effect of changes in boiling point and heat of vaporization on water level of the ECT need to be evaluated.

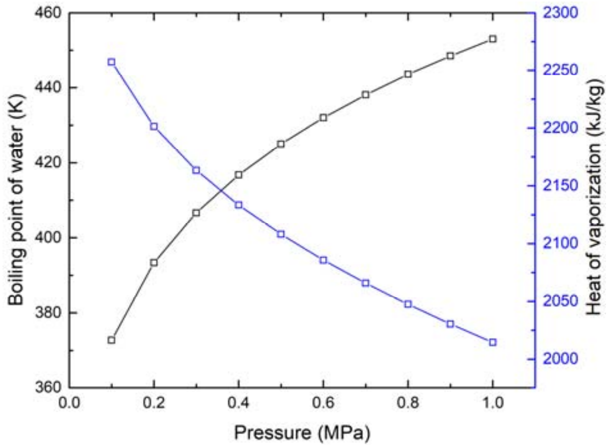

Fig. 1. Boiling point and heat of vaporization of water with pressure.

The objective of this study is to investigate the pressure effect of the ECT on the grace period of the PRHRS designed for a SMR called ATOM. The simulation was carried out by using the MARS-KS, a thermal hydraulic system analysis code. To consider the more realistic strategy, a relief valve was modeled at the top of the ECT with various open/close threshold pressures. The water level inside the ECT and temperature of primary system were investigated depending on the ECT pressure.

2. MARS-KS modelling

The reference reactor is an IPWR type SMR, which is similar to the SMART. The 4 helical-coiled SGs are installed in the vessel and connected to 2 ECTs. The simplified schematic of the PRHRS is shown in Fig. 2. When a hypothesized accident occurs, the PRHRS valves change the flow direction from the power generation cycle to the PRHRS loop. Major design parameters of the reference reactor and the PRHRS are presented in Table 1.

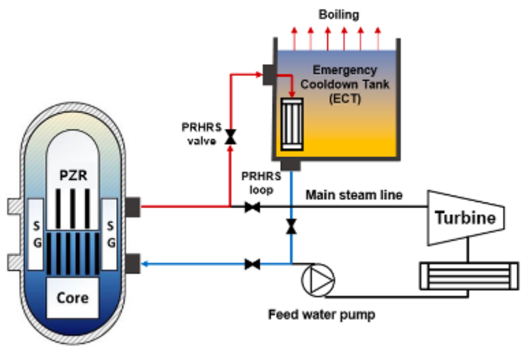

Fig. 2. Schematic diagram of the PRHRS.

Parameter	Value
Reactor parameters	
Reactor type	Integral PWR
Thermal power (MWt)	330
Electrical power (MWe)	100
Fuel material	UO_2
Fuel assembly	17×17
Operating pressure (MPa)	15
Core inlet temperature (K)	546
Core outlet temperature (K)	588
Core mass flow rate (kg/s)	1428.5
SG type	Helical tube
SG pressure (MPa)	4.42
PRHRS parameters	
ECT area (m^2)	20
Initial water level of ECT (m)	5
Length of HX-ECT (m)	2.5
Heat transfer area of HX-ECT (m^2)	28.3×4

Table 1. Design parameters of the reference reactor and the PRHRS.

To investigate the pressure effect in the ECT, MARS-KS code, the best estimation code developed by Korea Atomic Energy Research Institute, was used. A station blackout (SBO) was selected as an accident scenario for the transient simulation. The reactor trip was set to occur following 1,000 seconds of normal operation. In order to figure out the grace time according to the ECT pressure, a long-term simulation was performed until heat removal capability of the PRHRS was completely lost. For the normal operation of the reference reactor, the relative error between the design values and MARS-KS results was less than 1%. More details of the MARS-KS model are explained in Ref. [2].

Following the reactor shutdown, the valves 485, 585, 685, and 785 switch the flow paths to operate the PRHRS. The PRHRS parts of MARS-KS model used in Ref. [2] was modified to control the pressure in the ECT. As shown in Fig. 3, the ECTs were modified to have connection with atmosphere only through the relief valves 915 and 925. The hydrodynamic components pipe 850, 860, 865, and 870 consist of 25 volumes and the top five volumes are filled with non-condensable gas. The initial water level and the total length of the top 5 volumes in the ECT was set as 5 m and 2.5 m, respectively. The relief valves were located on the second volume from the top. To control the valve opening with the pressure in the ECT, a motor valve was utilized. To consider a broad pressure range, relief valves with arbitrary open pressure were considered. The opening conditions of the relief valve were set to 2, 4, 6, 8, and 10 bars. To determine the valve closing pressure, the change in grace time with various valve closing pressure conditions was investigated. The conditions for the relief valve were indicated in Table 2.

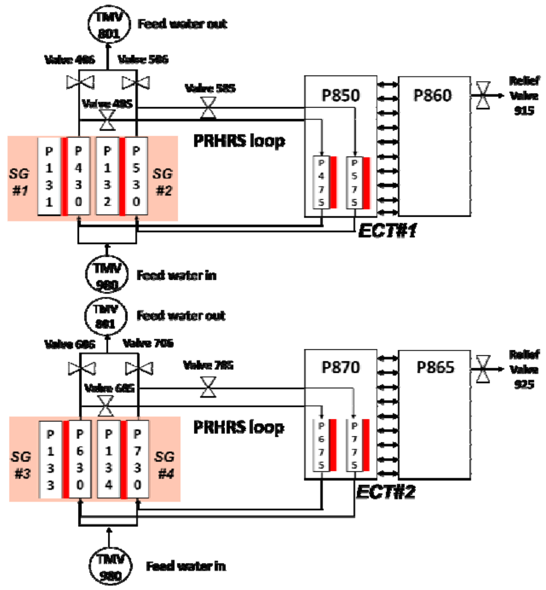

Fig. 3. MARS-KS nodalization of the PRHRS with relief valves.

Open pressure (bar)	Close pressure (bar)
2	1.1 / 1.3 / 1.5 / 1.7 / 1.9
4	3.1 / 3.3 / 3.5 / 3.7 / 3.9
6	5.1 / 5.3 / 5.5 / 5.7 / 5.9
8	7.1 / 7.3 / 7.5 / 7.7 / 7.9
10	9.1 / 9.3 / 9.5 / 9.7 / 9.9

Table 2. The investigated relief valve opening/closing pressures using MARS-KS.

3. Results and Discussions

3.1 Effect of valve closing pressure on the accident grace period

The grace period may vary depending on the valve opening/closing pressures since higher pressure in the ECT has both positive and negative effects in terms of continuous heat removal. Due to the complicated relationship between ECT pressure and the grace period, the effect of the valve close pressure was investigated. Figure 4 shows the change in grace time according to various pressure conditions during the accident. The results showed that the valve closing pressures of 1.9, 3.7, 5.3, 7.5 and 9.5 bar were found to show the longest grace period at opening pressures of 2, 4, 6, 8, and 10 bar, respectively. The effect of the ECT valve pressure on the cooling performance of the PRHRS were described in 3.2.

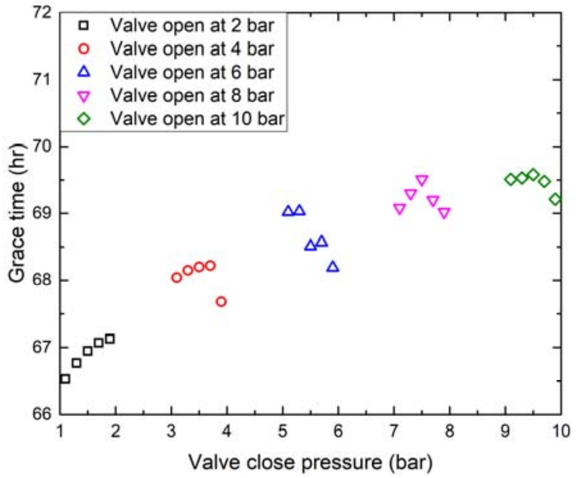

Fig. 4. Effect of the relief valve closing pressure on grace time.

3.2 Cooling performance of the PRHRS with the closed ECT

Figures 5 and 6 show change of the pressure and water temperature in the ECT, respectively. The pressure inside the ECT showed different behavior with the relief valve conditions. Until the temperature of the water inside the ECT reaches saturation point, as indicated in Fig. 1, which was limited by the relief valve condition, the pressure was increased due to thermal expansion and boiling. It is noted that the elapsed time until the temperature reached the opening condition of the relief valve was prolonged for higher opening pressure. Such behavior may contribute to extend the grace period of the ECT due to increased heat removal by sensible heat of water. After reaching the saturation point, the relief valve was opened and closed repeatedly slowly while venting out the steam generated in the ECT. The higher the opening pressure, the more frequent valve operation was observed. This is attributed to the larger amount of steam generation due to smaller heat of vaporization at higher pressure condition.

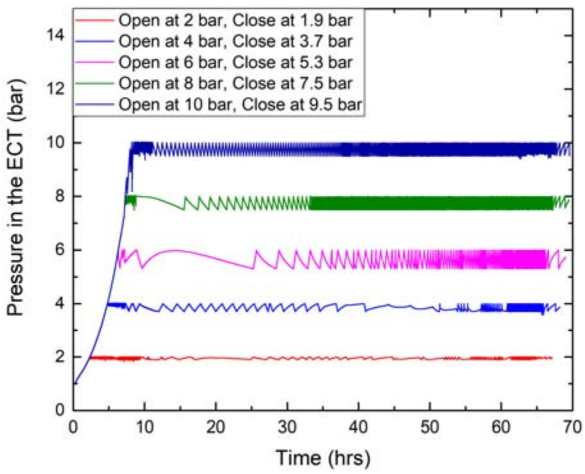

Fig. 5. Change of pressure inside the ECT with various open and close pressure conditions of relief valves.

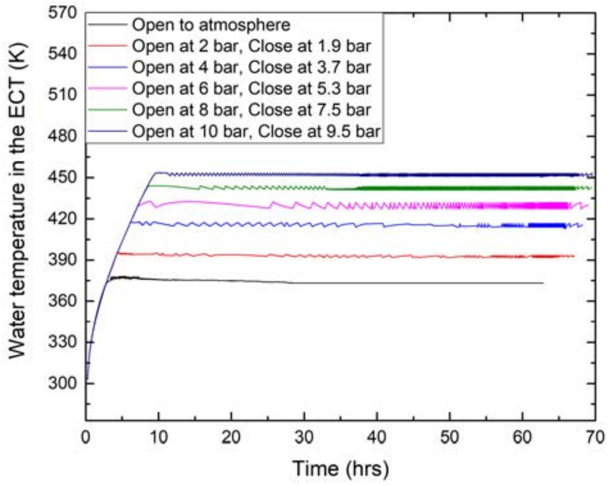

Fig. 6. Change of water temperature inside the ECT with various open and close pressure conditions of relief valves.

Figure 7 (a) shows the change in water level inside the ECT during accident. Unlike the ECT with opened condition, the ECTs with the relief valve show initial increase in water level. This is due to the increased water volume with increasing temperature. With higher opening pressure of the relief valve, the higher increment in water level was observed due to increased boiling point and specific volume of water. As the relief valve started to open, the water level gradually decreased due to escaping steam. At higher pressure condition, the decrease in the water level of the ECT also appeared later since it took longer to reach the saturation temperature. The decrease rate of the water level was faster for higher pressure condition due to smaller density and latent heat.

Figure 7 (b) shows the core exit temperature of primary coolant during the accident. The temperature experienced a sharp drop at 1,000 seconds due to reactor trip. As the temperature inside the ECT increased due to pressurization, the core temperature increased as well. When the ECT reached the opening pressure of the relief valve, the core temperature showed gradual decrease, which implies that the PRHRS successfully removes decay heat from the core. While the heat removal of the PRHRS was maintained, the temperatures at the core were lower than the boiling point of the coolant. Consequently, there was no issue of boiling crisis and overheating of fuel. However, when the ECT water level is lowered to 2.5 m, the heat exchanger started to be exposed resulting in deterioration of heat transfer performance. Accordingly, the core temperature began to increase. The temperature of the coolant rose sharply as the ECT water dried out. The time for the complete depletion of ECT water inventory were evaluated as 62.84, 67.13, 68.22, 69.03, 69.51, 69.59 hours for opened ECT, and ECTs with opening pressure of 2, 4, 6, 8, and 10 bars, respectively. It is noted that higher opening pressure of the relief valve successfully secured a few more hours than the open-type ECT.

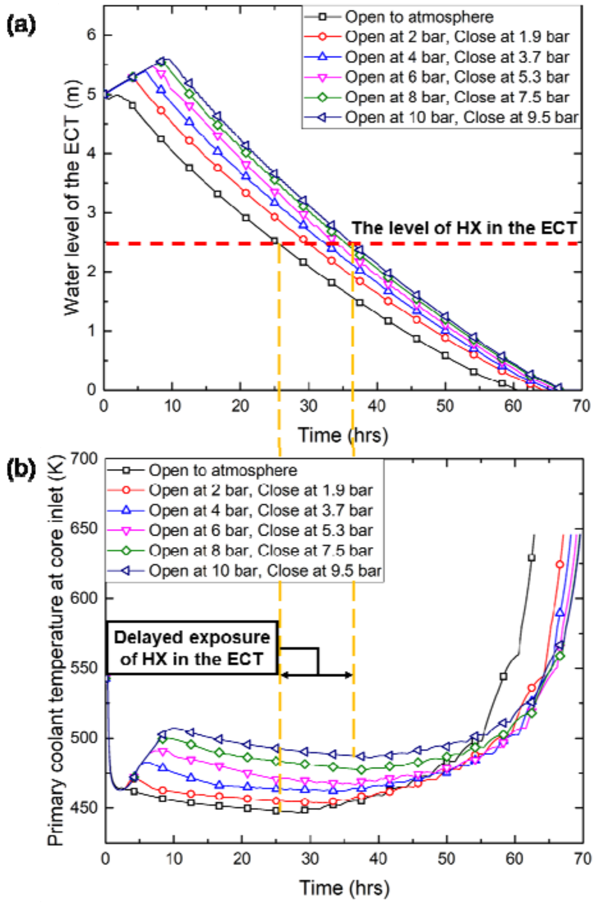

Fig. 7. Comparison of the various open and close pressure conditions of relief valves: (a) water levels of the ECT; (b) core inlet temperature.

From the foregoing results, the higher opening pressure of the ECT may exhibit an advantage on the performance of the PRHRS. However, the closed ECT with the relief valve requires more capital cost to endure the pressure and requires a strategy to supply additional water into the ECT from the outside under emergency situation. In spite of these setbacks, the close-type ECT with a relief valve can be feasible to delay the accident progression.

4. Conclusions

In this study, close-type ECT with a relief valve was suggested as a method to mitigate the accident progression. The effect of opening and closing pressure of the relief valve on the grace period of the PRHRS was investigated using MARS-KS code. The major outcomes from this work can be summarized as follows:

- The valve closing pressures of 1.9, 3.7, 5.3, 7.5 and 9.5 bar had the longest grace period for opening pressures of 2, 4, 6, 8 and 10 bar, respectively.
- The pressure increased due to thermal expansion and boiling in the closed ECT. For the higher opening pressure, the opening time of the first valve was delayed.
- The more frequent valve open/close operation was observed at the higher pressure because the steam generation was larger due to smaller heat of vaporization.
- The larger initial increase in water level in higher pressure condition was resulted from the increased boiling point of water. The relief valve also began to open later for the same reason.
- In higher pressure condition, the water level decreasing rate was faster due to smaller latent heat and density of water.
- The temperature of the coolant in primary system increased as the temperature inside the ECT increased due to pressurization.
- The time to complete loss of cooling capability of the PRHRS was delayed by a few hours with the higher pressure of the ECT.

Although this preliminary investigation suggested successful mitigation of accident progression, this concept of ECT may require more capital cost and modification of the accident mitigation strategy, which will be investigated for a future work.

Acknowledgments

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