Performance Analysis of Passive Residual Heat Removal System

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1. Introduction

While the operator can intervene in the active system, the passive system, once designed and installed, would be operated automatically. Because the passive system depends on the natural forces (e.g., gravitational force or natural circulation), of which the magnitude is small and uncertainties are significant, the special attention should be given in sizing and configuring the system. To assess the optimal condition for the passive system performance and the impact of the related uncertainties to the system reliability, the various methods have been developed, e.g., RMPS (Reliability Method for Passive Safety function) [1], REPAS (Reliability Evaluation of Passive System) [2] and APSRA (Assessment of Passive System Reliability) [3].

In this study, the performance of Passive Residual Heat Removal System (PRHRS) has been analyzed. Specifically, it has been focused on the effect of the working fluid inventory on natural circulation behavior and heat transfer performance. Firstly, the analysis framework has been setup by reviewing and adopting methods proposed in references [1-3]. Then, the key parameters related to PRHRS performance have been identified and examined with the carefully chosen accident scenarios. For that, MARS code has been used for numerical experiments. Sensitivity analysis has been conducted and the range of the optimal operational conditions has been investigated.

2. Passive System Performance Analysis

The framework of the performance analysis for passive system is presented in Fig.1, which is developed by adopting the part of the pre-proposed methods [1-3]. The first step is to identify the system function, mission and design criteria of the passive system. The phenomena related to passive system and the functioning mechanisms are addressed. Then, the accident scenario to examine the system performance is determined and the relevant parameters which govern the performance of the passive system are selected. Then, the system analysis can be performed by using a numerical simulation model. All relevant design characteristics should be modelled appropriately. In order to capture the uncertainty of physical model and boundary conditions, the sensitivity analysis would be necessary. The calculated performance of the passive system should be investigated with respect to the design requirements.

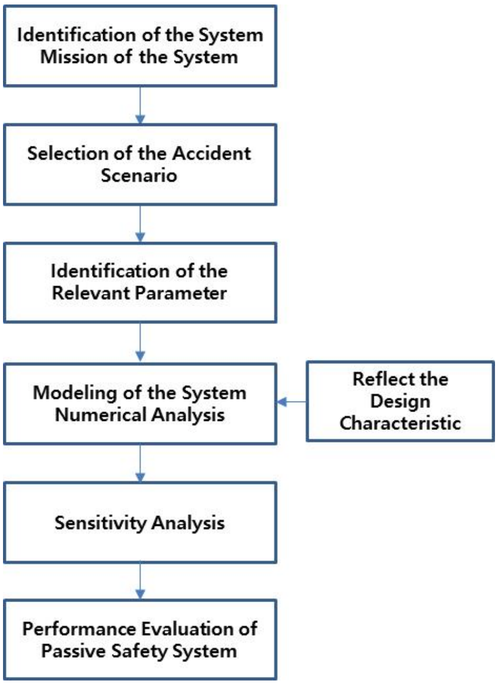

Fig.1 Passive System Performance Analysis Framework

3. Numerical Demonstration

The developed performance analysis framework has been applied to Passive Residual Heat Removal System PRHRS) which is adopted in innovative reactor concepts. In this study, the PRHRS of SMART (System-integrated Modular Advanced ReacTor) has been modeled by MARS-KS and used for performance analysis of passive system. It is important to note that the SMART is now under development and its design is not completed. Therefore, the system description and the results of PRHRS analysis in this paper should not be considered as the final one.

3.1 Identification of Passive Residual Heat Removal System

After reactor shutdown, the core residual heat and the sensible heat in the RCS is removed by PRHRS. The most important goal of PRHRS is the removal of the core heat and to reach and maintain the system to the safe shutdown. PRHRS consists of 4 trains and at least two trains of the PRHRS shall be operable during shutdown cooling operation. The schematic of the PRHRS is presented in Fig.2.

The core heat in the RCS is transferred to secondary system through the Steam Generator (SG) with the boiling and the heat of secondary system is transferred to the coolant in the ECT through the PRHRS heat exchanger with the condensation. Because boiling and condensing heat transfer coefficients (HTC) are larger than single-phase liquid HTC, the boiling-condensation nature circulation is most efficient mechanism. It is optimal condition that the saturated vapor exists in SG outlet to ECT inlet and the saturated water exists in ECT outlet to SG inlet. If the pressure increases, the saturation temperature would be increased and the single phase heat transfer would occur; thus, the performance of PRHRS would be degraded.

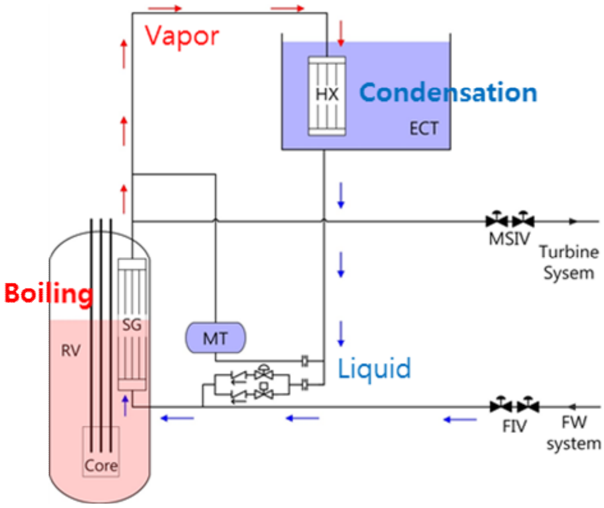

Fig.2 Schematic of the PRHRS

3.2 Selection of Accident Scenario

The reactor trip accident was selected as reference accident. This accident scenario is proper to evaluate the PRHRS performance because the decay heat of core is only removed by PRHRS.

3.3 Identification of Relevant Parameter

If the difference between surface temperature of heat exchanger is higher than about 5℃, the nucleate boiling is made up. In nucleate boiling regime, the heat transfer from heat exchanger to coolant is further higher than single phase heat transfer. Saturation temperature of PRHR is determined by system pressure which is influenced by inventory charging of PRHRS, which is varied by signal delay, valve stroke time, etc. Consequently, the relevant parameter is selected to the secondary inventory. The independent variable of this parameter is charging time by signal delay.

3.4 Modeling of System and Numerical Analysis

MARS-KS model has been developed for the thermal-hydraulic analysis under reactor trip accident. The reactor trip accident occurs by loss of the power or reactor trip signal. After reactor trip, core decay heat is removed by secondary side using PRHRS, and RCS coolant is supplied by Core Make-up Tank (CMT).

If reactor trip occurs, turbine tripped after 5.0s and then PRHRAS (PRHR Actuation Signal) occurs by high steam line signal. Then, MFIV/MSIV are closed, CMT valve opened, PRHRS actuation is initiated. The major event timings of the reference case are summarized in in Table 1.

Table.1 Major Event Timing

Event	Time [s]
Reactor trip	0.001
Turbine trip	5.0
Steam Line High Pressure signal PRHRAS occur	13.43
Feedwater flow shut off MFIV close	20.77

3.5 Sensitivity Analysis for Charging Time.

The simulations were conducted for evaluating performance of the PRHRS according to charging inventory. Charging inventory is the relevant parameter for dominating performance of the PRHRS, but this parameter has uncertainties. Turbine trip time and PRHRAS can be delayed and the secondary inventory can be increased.

In this analysis, the inventory of secondary side was adjusted by timings of feedwater flow shut off. Fig.3 shows the secondary inventory for charging time. Secondary inventory ramp up as the charging time increases. As can be seen in Fig.4, Fig5 for charging time +30, +40 and +50s cases, heat transfers are degraded compared with +5, +10s cases and cladding temperatures and RCS pressures are higher. For charging time +40 and +50 seconds cases, pressurizer safety valve (PSV) is opened because RCS pressure is over 17.3 MPa (Fig.6).

Fig.7 presents the void fraction in SG outlet. In base case, +5 and +10 charging case, almost mass is vaporized the energy is stored as latent heat in steam line. The heat vaporization is efficient heat transfer mechanism. However, in +30, 40, +50 charging time case, void fraction of secondary SG outlet is under 0.6, which means most of the inventory exists in liquid phase. Phase transition, liquid to vapor occurs little and the heat is transferred by nearly single phase. Single phase heat transfer is less efficient compared with vaporization and heat transfer between SG and RCS is degraded. That means the PRHRS performance is degraded by over-charging.

In typical PWR, auxiliary feedwater supply is controlled by SG level and heat transfer by vaporization can be available at any condition. But In PRHRS, the performance is dominant by the secondary inventory which is determined by feedwater charging time.

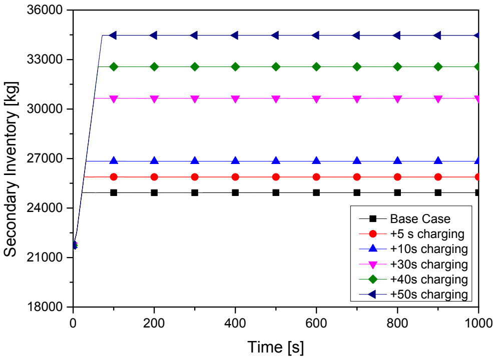

Fig.3 Secondary Inventory Comparison

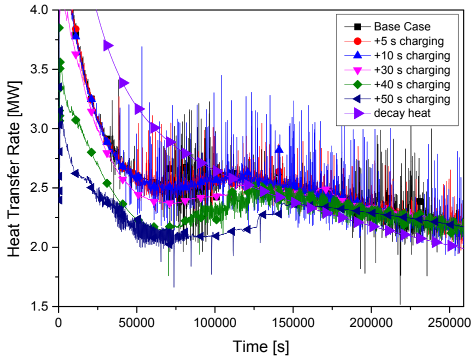

Fig.4 Heat Transfer Rate Comparison

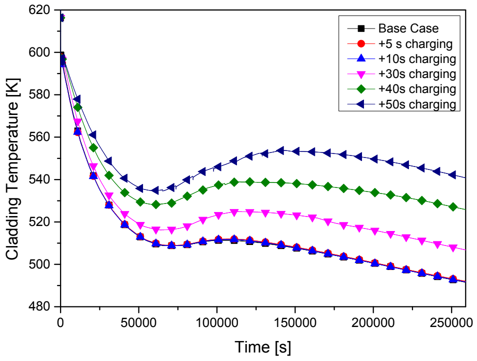

Fig.5 Cladding Temperature Comparison

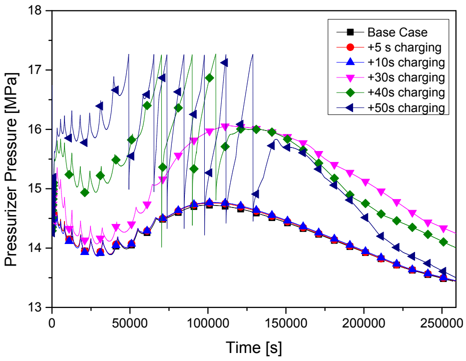

Fig.6 RCS Pressure Comparison

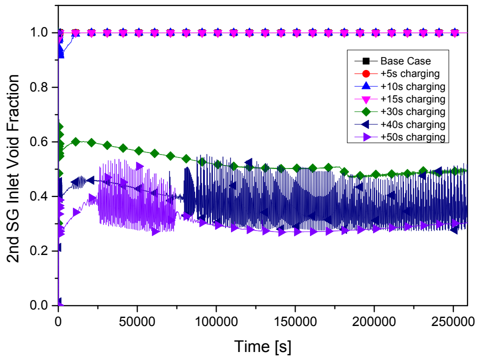

Fig.7 PRHRS Void Fraction Comparison

4. Conclusion

The performance analysis of PRHRS has been conducted. Accident scenario is selected as reactor trip accident and relevant parameter is secondary inventory. The numerical analysis using MARS-KS code under reactor trip accident and sensitivity analysis according to charging time was conducted. As a result of analysis it has been observed that the PRHRS performance could be degraded depending on the operation conditions. If the working fluid (i.e., water inventory) is over-charged, the natural circulation could not be established sufficiently and the heat transfer would be deteriorated. For optimal PRHRS performance the uncertainty factor (e.g., signal delay) should be eliminated.

5. References

[1] Marques *et al.*, Methodology for the performance evaluation of a passive system and its integration into a Probabilistic Safety Assessment, Nuclear Engineering and Design, 2008. 235, 2612-2631.
[2] Jafari *et al.*, Performance evaluation of a natural circulation system, Nuclear Engineering and Design, 2008. 224, 79-104.
[3] Nayak *et al.*, Passive system performance analysis using the APSRA methodology, Nuclear Engineering and Design, 2008. 238, 1430-1440.
[4] KAERI, MARS Code Manual, 2009
[5] John Willy & Son, Heat and Mass Transfer, 2011