Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

Comparative Performance Analysis of SMART Passive Residual Heat Removal System using MARS-KS and MELCOR

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1. Introduction

SMART(System-Integrated Modular Advanced ReacTor) is a small-sized integral type PWR. SMART adopts the integral design concept of containing most of the primary circuit components in a single Reactor Pressure Vessel (RPV) [1]. Due to this integral arrangement of the primary system, SMART can fundamentally eliminate the possibility of Large Break Loss of Coolant Accidents (LBLOCAs). Besides the inherent safety characteristics achieved by design, the safety is further enhanced by the highly reliable engineered safety system, e.g., passive residual heat removal system (PRHRS) and passive safety injection system (PSIS).

PRHRS removes the RCS heat by the natural circulation in emergency situations where normal steam extraction or feedwater supply is unavailable and cools the RCS to the safe shutdown condition. PRHRS consists of four independent trains and each train is composed of one emergency cooldown tank (ECT), one PRHRS heat exchanger (PHX) and one PRHRS makeup tank (PMT). Each train is connected to a set of two steam generators (SGs). When an accident occurs, the passive residual heat removal actuation signal (PRHRAS) is generated by the SMART protection system (SPS). Upon receipt of the signal, the PRHRS isolation valves are open automatically and the main steam isolation valves (MSIVs) and feedwater isolation valves (FIVs) are closed simultaneously. Then a closed loop of a natural circulation is formed through the SGs, the PHX and the connecting pipelines. The schematic of PRHRS is shown in Fig. 1.

Passive systems rely on the natural forces; thus, once the system is installed, it would be functioning as it is designed and it would be very hard for operators to intervene. Due to wide range of variability in accident scenarios and plant conditions, the passive system should be validated extensively to make sure its functionality. For last decades, extensive experimental, analytical studies have been conducted to verify the advanced design features implemented into SMART [2-10]. Especially, the performance of PRHRS has been validated experimentally and the experimental results have been compared to MARS-KS code calculations. Then, MARS-KS code has been used to analyze the dynamic behaviors of PRHRS and SMART under the accident conditions.

This study has been motivated by comparing accident simulation results for level 1 and level 2 probabilistic safety assessment (PSA). Assuming the MARS-KS code is sufficiently validated and verified, MARS-KS has been used for the success criteria analysis for level 1 PSA. However, in order for the success criteria analysis for level 2 PSA, capabilities for simulating phenomena related to severe accidents would be required. MELCOR 2.2 has been used for severe accident analysis, however, it has not been validated for PRHRS of SMART extensively. In this study, MELCOR 2.2 has been validated by MARS-KS. The condensation heat transfer models implemented in MELCOR 2.2 and MARS-KS have been reviewed and the simulation results have been compared.

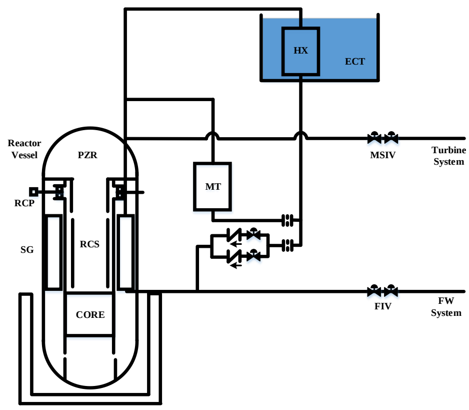

Fig. 1. Schematic of SMART PRHRS

2. Comparison of MARS-KS and MELCOR 2.2

MARS-KS has been developed by KAERI primarily for analyzing design basis events such as nuclear power plant transients [11] and has been validated in various studies for SMART passive safety systems. And MELCOR 2.2 developed by Sandia National Laboratory is composed of an executive driver and a number of packages for each specific phenomenon and function [12].

Both codes are based on the two-fluid formulation with "control volume" approach (i.e., no pre-defined nodalization). There are differences in numerical scheme, therefore, it can be found that the different correlations are introduced in heat transfer calculations.
Because the performance of passive system depends on the natural circulation, which is very sensitive on the

heat transfer characteristics, those differences can change the simulation results significantly. Both codes adopt film model in condensation heat transfer. Comparison table of the condensation heat transfer model is presented in Table I. And the result of film thickness calculation in 3 ~ 15 MPa saturated steam condition is presented in Table II. Condensation heat transfer coefficient of PHX is inversely proportional to film thickness. Therefore, it can be expected that PHX heat removal rate in MELCOR 2.2 will be evaluated larger than MARS-KS.

TABLE I: Comparison of Condensation Heat Transfer Model

Category	MARS-KS	MELCOR 2.2
Condensation Heat Transfer model	Film model $h_{cond.} = \frac{K_f}{\delta}$, $\delta = \left(\frac{3\mu_f \Gamma}{g \rho_f}\right)^{1/3}$, $\Gamma = \frac{\dot{m}_f}{\pi D_i}$	Film model $H_f = max(H_{f,corr}, K_f / \delta)$ $H_{f,corr} = [K_f / (v_f / \rho_f)^2 / g]^m Nu_f$
	where, $h_{cond.}$: condensation heat transfer coefficient [$W/m^2 \cdot K$] K_f : fluid thermal conductivity [$W/m \cdot K$] δ : film thickness [m] μ_f : fluid viscosity [$kg/m \cdot \sec$] ρ_f : fluid density [kg/m^3] Γ : liquid mass flow per unit periphery [$kg/\sec$]	D_i : inside diameter [m] H_f : liquid film heat transfer coefficient $H_{f,corr}$: function depends on surface geometry v_f : kinematic fluid viscosity [$m^2/\sec$] g : acceleration of gravity [$m/\sec^2$] Nu_f : film Nusselt number

TABLE II: Result of Film Thickness Calculation

Pressure [MPa]	Film Thickness [m]	
	MARS-KS	MELCOR2.2
3	0.00187	0.00040
4	0.00205	0.00044
5	0.00212	0.00049
6	0.00223	0.00053
7	0.00233	0.00057
8	0.00243	0.00060
9	0.00253	0.00064
10	0.00263	0.00068
11	0.00272	0.00071
12	0.00282	0.00075
13	0.00292	0.00080
14	0.00302	0.00084
15	0.00313	0.00089

3. Numerical Analysis

Firstly, simplified PHX has been modeled by MARS-KS and MELCOR to compare the condensation heat transfer rate of PHX in steady-state conditions.

Secondly, SMART has been modeled in details by MARS-KS and MELCOR. Vessel including internal components, primary side, and secondary side including steam generators are modeled. In addition, PRHRS are also modeled in details. The same nodalization (e.g., same number of control volumes and sizes) has been used

3.1 Simplified PHX Model

The schematic nodalization of PHX is presented in Fig. 2. It is assumed that steam reservoir and ECT volume is infinite and non-condensable gas does not exist. The operating pressure range of PRHRS is from 3 to 15 MPa .Therefore, 13 cases are analyzed in both MAR-KS and MELCOR 2.2. Fig. 3 and Fig. 4 show the heat transfer rate and the flow rate of the PHX resulting from Fig. 2. The higher steam temperature and pressure cause the larger flow and heat removal rate of PHX. The flow rate and PHX heat removal rate in MELCOR 2.2 is evaluated larger than MARS-KS.

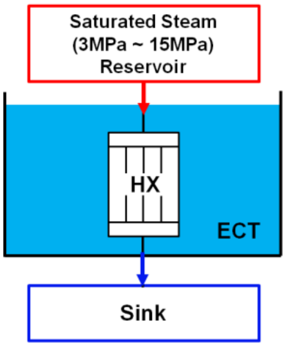

Fig. 2. Schematic Nodalization of PHX

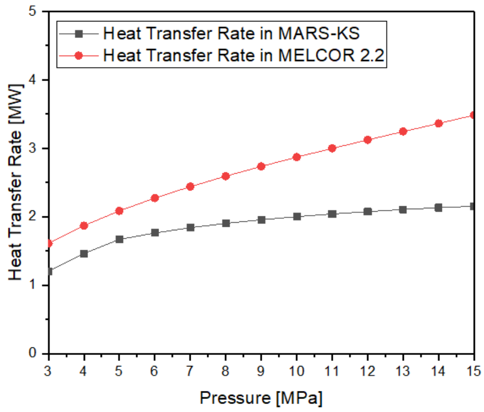

Fig. 3. Heat Removal Rate of PHX

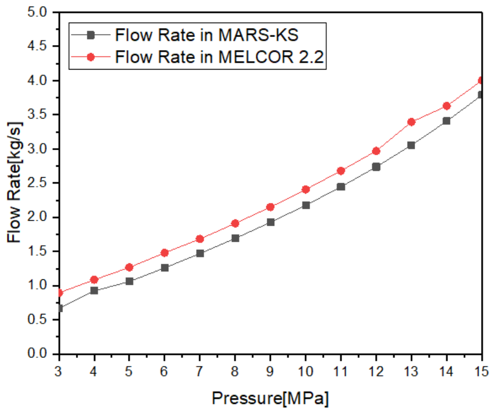

Fig. 4. Flow Rate of PHX

3.2 SMART Model

In Fig. 5, the nodalization of SMART is presented. Fig. 6 through Fig. 8 show transient behaviors of the RCS and PRHRS in a Loss of Main Feedwater (LOMF) accident. The reactor and RCP are assumed to be tripped immediately after the event initiation. The passive residual heat removal actuation signal (PRHRAS) is generated by the low feedwater flow rate at 0.0 hours, and by the PRHRAS, the main steam isolation valves and feedwater isolation valves (MSIVs/FIVs) begin to close and the PRHRS outlet isolation valves begin to open, which isolate the SGs from turbine and connect the SGs to the PRHRS. It is assumed that 2 trains of PRHRS are available. As a result, the core temperature is not increased and the accident is not progressed further in both code analyses.

Though both codes estimate that the core would not be damaged and the accident is mitigated by 2 trains of PRHRS operation, the performance of PRHRS is evaluated quite differently. The decay heat in core would be delivered to the secondary side of SG by heat transfer via SG tubes and be removed by heat transfer in PHX. Therefore, the heat transfer is the most important mechanism in accident progression. Since MARS-KS and MELCOR have different heat transfer calculation correlations and scheme, the simulation results are differentiated.

As can be seen from the Fig. 3 and 4, the condensation heat transfer of PHX calculated by MELCOR 2.2 is larger than the one by MARS-KS. So, it is likely to expect that the MARS-KS would estimate conservatively. However, in case of LOMF as shown in Fig. 6 and 8, the PRHRS performance calculated in MARS-KS is higher than the one by MELCOR 2.2 at 72 hours. It is because the higher condensation heat transfer of PHX reduces the pressure and temperature of PRHRS rapidly at the early stage of the accident and the temperature difference between PRHRS heat source and sinks is lowered. On the other hands, in MARS-KS calculations, the natural circulation flow is established at the higher temperature difference, which incurs the lower PRHRS temperature and pressure.

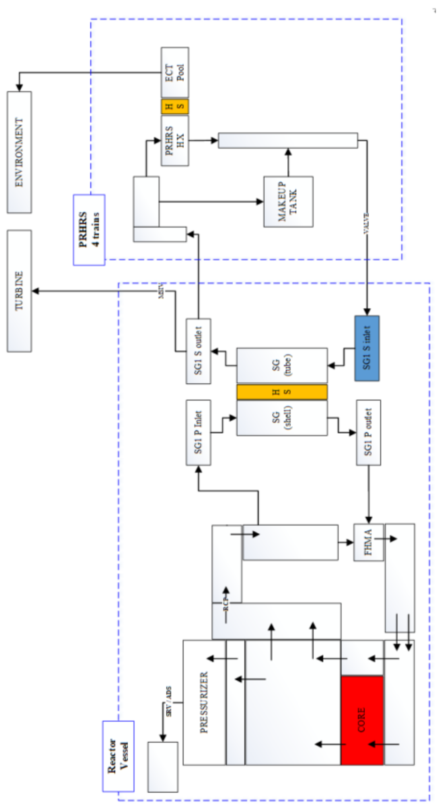

Fig. 5. SMART Nodalization of MARS-KS and MELCOR

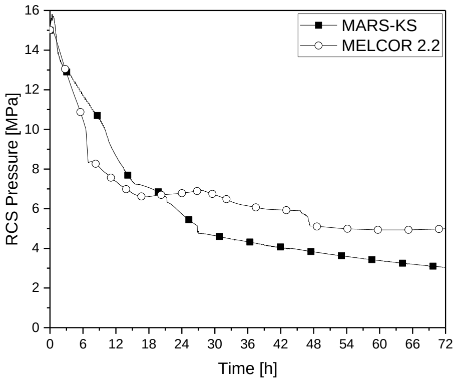

Fig. 6. LOMF – RCS Pressure

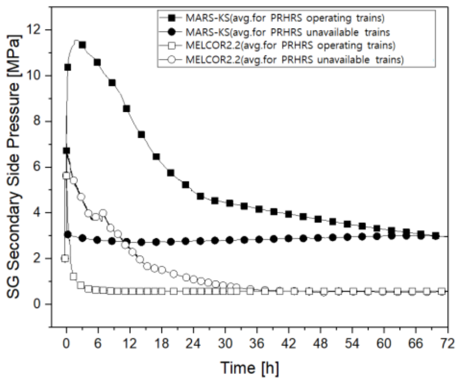

Fig. 7. LOMF – SG 2nd side Pressure

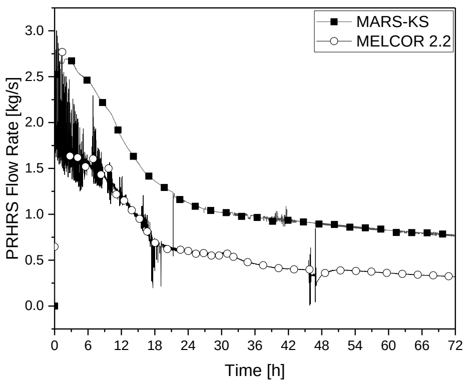

Fig. 8. LOMF – PRHRS Flow Rate

4. Conclusions

MELCOR 2.2 is compared to MARS-KS in view of SMART PRHRS analysis. Heat transfer correlations related to the major operation mechanisms of PRHRS are reviewed and numerical results are compared. It has been shown that the passive system performance would be changed sensitively according to the system operating conditions and the changed passive system performance would feedback on the system operating conditions. Estimates simply based on comparisons of heat transfer models or steady-state numerical test results would mislead the prediction on the system performance and the accident progression. To guarantee the intended functionality of the passive safety system, special caution should be given by investigating the dynamic behavior thoroughly.

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