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Simulation of an SBLOCA Test of Shutdown Cooling System Line Break with the SMART-ITL Facility using the MARS-KS Code

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1. Introduction

SMART (System-integrated Modular Advanced ReacTor) [1] was designed by KAERI as an integral type reactor and received standard design approval by the Korean regulatory body in July 2012. In this SMART design, a reactor pressure vessel contains the main components including a pressurizer and steam generators without any large-size pipes. An LBLOCA (Large-Break Loss of Coolant Accident) was inherently eliminated in the design stage. The SMART design has a thermal power of 330MW. Its core exit temperature and pressurizer pressure are 323℃ and 15MPa during normal operating conditions, respectively.

An integral-effect test loop for SMART (SMART-ITL), called FESTA (Facility for Experimental Simulation of Transients and Accidents) [2, 3], was designed to simulate the integral thermal-hydraulic behavior of SMART. The objectives of SMART-ITL are to investigate and understand the integral performance of reactor systems and components, and the thermal-hydraulic phenomena occurring in the system during normal, abnormal, and emergency conditions, and to verify the system safety during various design basis events of SMART. SMART-ITL with four steam generators and PRHRS, has an advantage for a multi-loop effect compared with VISTA-ITL [4] with a single loop. The integral-effect test data will also be used to validate the related thermal-hydraulic models of the safety analysis code such as TASS/SMR-S [5] which is used for a performance and accident analysis of the SMART design. In addition, a scoping analysis [6] on the scaling difference between the standard design of SMART and the basic design of SMART-ITL was performed for an SBLOCA (Small-Break Loss of Coolant Accident) scenario using a best-estimate safety analysis code, MARS-KS [7]. This paper introduces a comparison of an SBLOCA test of a shutdown cooling system line break using SMART-ITL with its post-test calculation using the MARS-KS code.

2. Scaling and design of the SMART-ITL

2.1 Scaling of the SMART-ITL

SMART-ITL was designed following a three-level scaling methodology consisting of integral scaling, boundary flow scaling, and local phenomena scaling. Its height is preserved to the full scale, and its area and volume are scaled down to 1/49 compared with the prototype plant, SMART. The maximum core power is 2.0MW, which is about 30% of the scaled full power. The design pressure and temperature of SMART-ITL can simulate the maximum operating conditions, that is, 18.0MPa and 350℃. The scaling ratios adopted in SMART-ITL with respect to SMART are summarized in Table I.

Table I: Major scaling parameters of the SMART-ITL

Parameters	Scale Ratio	Value
Length	l_{0R}	1/1
Diameter	d_{0R}	1/7
Area	d_{0R}^{2}	1/49
Volume	$l_{0R}\ d_{0R}^{2}$	1/49
Time scale, Velocity	$l_{0R}^{1/2}$	1/1
Power, Volume, Heat flux	$l_{0R}^{-1/2}$	1/1
Core power, Flow rate	$d_{0R}^{2}\ l_{0R}^{1/2}$	1/49
Pump head, Pressure drop	l_{0R}	1/1

2.2 Basic Design of the SMART-ITL

Fig. 1 shows a schematic diagram of the SMART-ITL facility, which can simulate the operational and accidental transients that occur in the integral effect test loop in view of thermal hydraulics. SMART-ITL consists of a primary system, four steam generators (SGs), a secondary system, 4 trains of a passive residual heat removal system (PRHRS), 4 trains of a safety injection system (SIS), 2 trains of a shutdown cooling system (SCS), a break simulator (BS), a break flowrate measuring system (BMS), and auxiliary systems. The primary system includes a reactor pressure vessel (RPV), a steam pressurizer, shell sides of four SGs, and four reactor coolant pumps (RCPs) to simulate asymmetric loop effects. An annular downcomer design is applied at the upper part to simulate a multi-dimensional effect. However, as the scaled-down annular downcomer of SMART-ITL is not enough to contain the SGs, four SGs are installed outside of the RPV using two connecting pipes above and below each SG like hot and cold legs, respectively, which facilitates relevant measurements. In the secondary system, four steam lines are lumped into a direct condenser tank where the steam generated by four SGs is condensed and the condensed feedwater is again injected into the SGs.

The PRHRS is composed of four trains, each of which includes an emergency cooldown tank (ECT), a heat exchanger (HX), a makeup tank (MT), several valves, and connecting pipes. It is connected to feedwater and steam lines of the secondary system, and a natural circulation flow path is formed by opening the isolation valves by the actuation signal. It was designed to have the same pressure drop and heat transfer characteristics, and arranged to have the same elevation and position as those of SMART to preserve the natural circulation phenomenon. In addition, the diameter, thickness, pitch, and orientation of the heat exchanger tubes of the SMART-ITL facility are the same as those of SMART. During the PRHRS operation, the superheated steam generated from the steam generator secondary side is directed to and condensed in the PRHRS heat exchangers by natural circulation. The condensed water flows downward through the PRHRS condensate line and returns to the feedwater line. The condensing heat is transferred to the ECT, which is filled with water and functions as an ultimate heat sink.

The SIS and SCS can simulate several operation modes such as safety injection, long-term cooling, shutdown cooling, and recirculating operations. The BS consists of a quick opening valve, a break nozzle, and instruments. The BMS collects the break flow and maintains a specified pressure to simulate the back-pressure of the containment. A separator in the BMS separates a liquid phase from a two-phase break flow, and each separated flow rate in a single phase condition is measured by a different measuring technique. The separated liquid and gas flow rates are measured respectively by weighing a mass of accumulated water and by a dedicated flowmeter. SMART-ITL is also equipped with some auxiliary systems such as a makeup water system (MWS), a component cooling water system (CWS), a compressed air system (CAS), a steam supply system (SSS), a vacuum system (VS), and a heat tracing system (HTS).

The control and data acquisition system of SMART-ITL has been built with a hybrid distributed control system (DCS). The input and output modules are distributed into 5 cabinets, which are controlled by two central processing units (CPUs). The raw signals from the field are processed in a system server and the converted signals are monitored and controlled through a human-machine interface (HMI), which consists of 52 processing windows classified according to the SMART fluid system.

The number of instruments is up to 1,014 at present. Instrument signals can be categorized according to the instrument type, such as the temperature, the static pressure, the collapsed water level, the differential pressure, the flow rate, the power, and the weight. The core heater cladding temperatures are measured for several radial and axial locations with more than 260 thermocouples, and the fluid temperatures in the RPV are measured with more than 100 thermocouples.

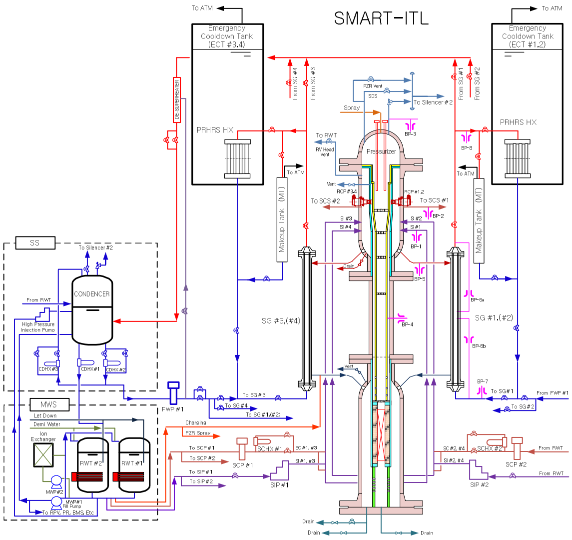

Fig. 1. Schematic diagram of the SMART-ITL Facility

3. A SCS Line Break Test and Its Simulation with MARS-KS

3.1 SMART-ITL Nodalization

A post-calculation was performed for the experimental SBLOCA scenario using a best-estimate safety analysis code, MARS-KS. During the simulation of the SBLOCA, it is assumed that the break occurs on the SCS piping nozzle at the same position. In addition, the set-point and sequence of events in the SBLOCA scenario were the same as those used in the test, as shown in Table II.

The nodalization of the SMART-ITL was based on an isometric drawing and design reports provided by KAERI. In addition, some assumptions and modifications were made. A MARS-KS nodalization diagram for SMART-ITL is represented in Fig. 2. The nodalization for a MARS-KS simulation includes all reactor coolant systems, a safety injection system, and a secondary system including the PRHRS.

Table II: Major sequence of SBLOCA simulation test

Event	Trip signal and Set-point SMART-ITL
Break	
LPP set-point	PZR Press = P_{LPP}
LPP reactor trip signal - FW stop - RCP coastdown	LPP+1.1 s
Control rod insert	LPP+1.6 s
PRHR actuation signal	LPP+2.34 s
PRHRS IV open FIV close	PRHRAS+5.0 s
MSIV close	PRHRAS+15.0 s
Safety injection signal	PZR Press = P_{SIAS}
Safety injection start	SIAS+30.0 s

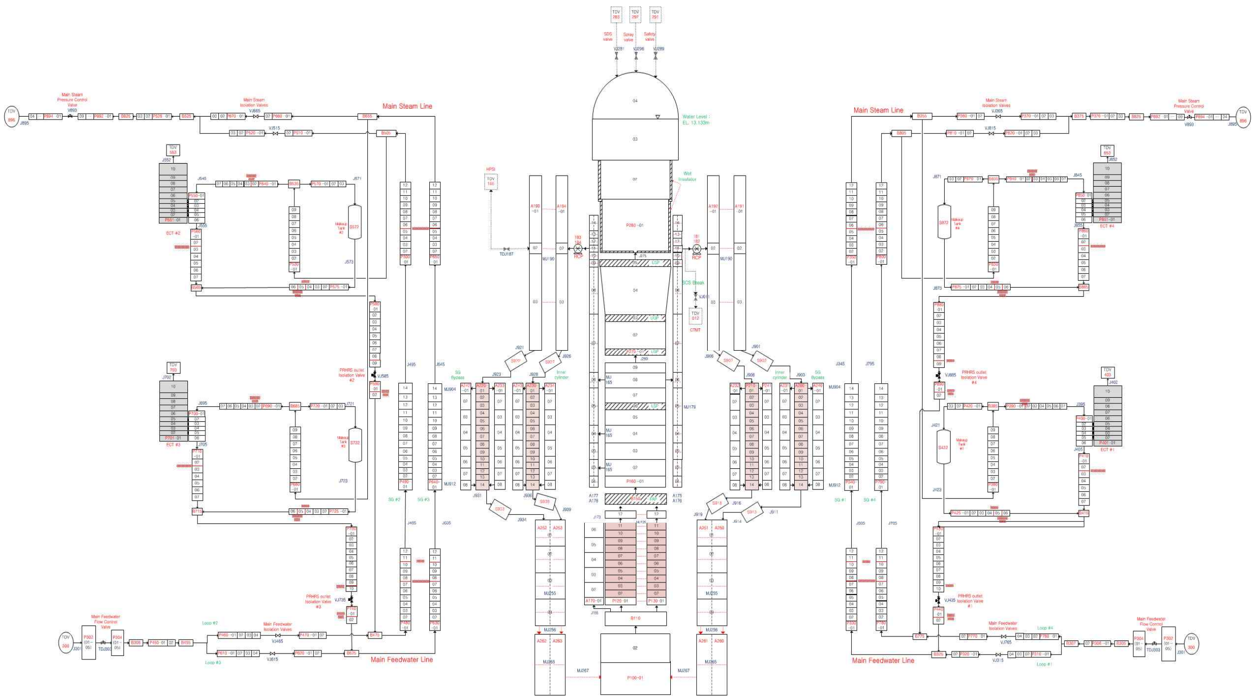

Fig. 2. Nodalization diagram of SMART-ITL for MARS-KS Simulation

Table III: Comparison of the major parameters at a steady state condition

Parameter	SMART-ITL (Target value)	SB-SCS-01 (Measured value)	MARS-KS (Calculation)
Power (kW)	1346.9	1487.09	1487.09
PZR press.(MPa)	15.0	15.0	15.0
1^{st} flowrate(kg/s)	8.53	8.871	8.957
SG 1^{st} inlet temp.(℃)	323.0	321.62	321.37
SG 1^{st} outlet temp.(℃)	295.7	297.88	296.34
FW flow-rate(kg/s)	0.6563	0.6577	0.6577
SG 2^{nd} outlet press.(MPa)	5.2	4.96	4.96

* Heat loss in Reactor Coolant System is included.

3.2 Simulation Condition

For the SBLOCA scenario of the shutdown cooling system line break, the break line is assumed to be one of the available shutdown cooling system lines, and only one of the four safety injections is assumed to be active based on a single failure assumption. The safety injection flow rate of SMART-ITL is 1/49 that of SMART with the same pre-specified safety injection pump characteristics. The break size is set to be reduced according to an area scale ratio of 1/49.

3.2 Comparison of SBLOCA Test with MARS-KS Simulation

Table III shows a comparison of the major parameters between the test and simulation under a steady state condition. The primary system flow rates of the test and simulation for a 20% core power are 8.871 kg/s and 8.957 kg/s, respectively. The secondary system flow rates of the test and simulation are the equal at 0.6577 kg/s. The primary system pressure of a 20% core power condition is 15.0MPa. The inlet/outlet temperatures of the steam generator's primary side in the test are 321.62℃ and 297.88℃, respectively. Those in the simulation are 321.37 ℃ and 296.34 ℃, respectively.

Table IV shows the test results of the major sequence for the SBLOCA simulation test. When a SCS line was broken, the RCS began to be depressurized. As the pressurizer pressure reached the LPP trip set-point (P_{LPP}) after the SCS line break, the reactor trip was generated about 0.5 s after the LPP signal, which was generated at 125 s in the test and 210 s in the code simulation after the break. Consequently, with the reactor trip signal, the feed water was stopped and the reactor coolant pump started to coast-down. It was shown that the PRHRS actuation signal occurred. The safety injection water was injected 30 s after the safety injection actuation signal (SIAS). The individual signal is sequentially actuated. A LPP set-point of the simulation is, however, reached about 85 s later than that of the test. This time gap is sustained until the safety injection starts. It means that the amount of the depressurization is a little fewer in the simulation than in the test during the beginning stage of the break.

Table IV: Test results of major sequence for SBLOCA

Event	SB-SCS-01 Time After Break (seconds)	
Sequence	Test	Simulation
Break	0.0	0.0
LPP set-point	125.0	210.1
LPP trip signal - FW stop - RCP coast-down	128.0	211.2
Reactor trip-curve start		211.7
PRHR actuation signal	130.0	212.5
PRHRS IV fully open	135.0	217.5
FWIV fully close MSIV fully close	134.0 150.0	217.5 232.5
Safety injection signal	641.0	650.6
Safety injection start	671.0	680.6

The steady-state conditions were operated to satisfy the initial test conditions presented in the test requirement, and its boundary conditions were properly simulated.

Figs. 3-8 show the variations of the major parameters. The decay power curve and safety injection flow rate, shown in Fig. 3 and Fig. 4, were well provided as the boundary conditions for the test and code simulation.

Fig. 5 shows the pressure behavior of the primary system. The primary pressure decreased rapidly during the single-phase liquid blowdown period. The pressure decrease was slowed down during the two-phase discharge period, and the pressure then decreases gradually during the single-phase steam blowdown period.

Fig. 6 shows the primary system temperature. As the SCS line break occurs and the primary pressure decreases dramatically, the primary temperature in the inlet of the SGs also decreases along with the saturation temperature. The temperature range in the outlet is under the saturation temperature.

Fig. 7 shows the secondary system pressure. In the beginning of the transient, the pressure increases rapidly. It decreases gradually after arriving at the peak pressure. As a feedwater pump was stopped, the PRHRS was actuated, and the feed-water isolation valve and main steam isolation valve were closed, the secondary pressure increased. After a natural circulation of the secondary system by the balance between the steam generators and PRHRS started up, it decreased.

Fig. 8 shows the secondary system flow rate. As the PRHRS system operates, the feed-water flow rate shows a dramatic change at the beginning, and natural circulation is achieved within a few seconds. After that, the natural circulation flow rate shows a gradual decrease at a constant rate. The flow rate in the code simulation is a little smaller than in the test. The flow rate under a natural circulation condition is dependent on the heat balance between the heat exchanger and the SG, and the hydraulic resistance in the loop. It is supposed that the hydraulic resistance of the test facility is different from that of the code simulation. With the operation of the PRHRS, a two-phase natural circulation flow formed inside the PRHRS loop.

Test and code simulation of the SBLOCA for a shutdown cooling system line break (SB-SCS-01) were performed. The experimental results were properly reproduced by the code analysis using the MARS-KS.

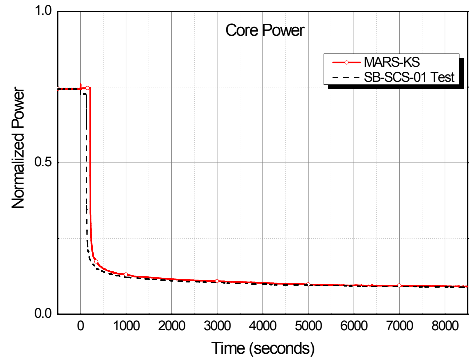

Fig. 3. Core Power

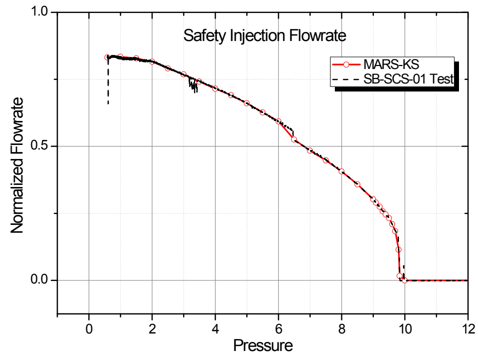

Fig. 4. Safety Injection Flowrate

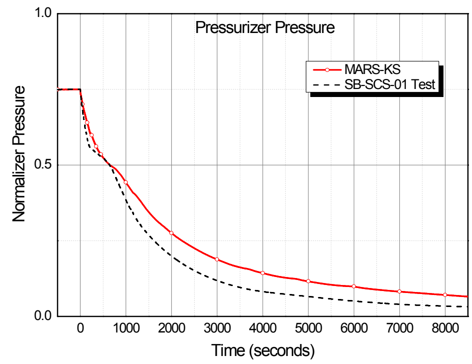

Fig. 5. Pressurizer Pressure

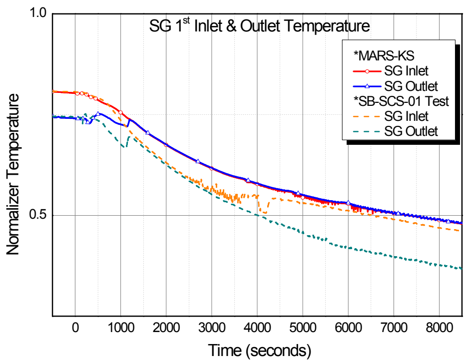

Fig. 6. SG 1st Temperature

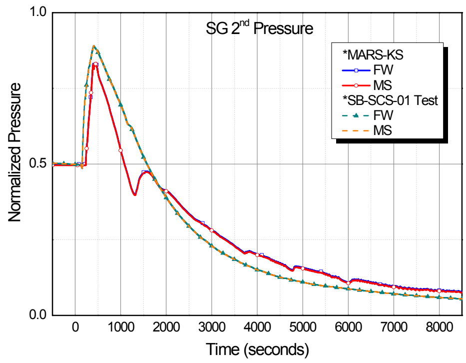

Fig. 7. 2nd System Pressure

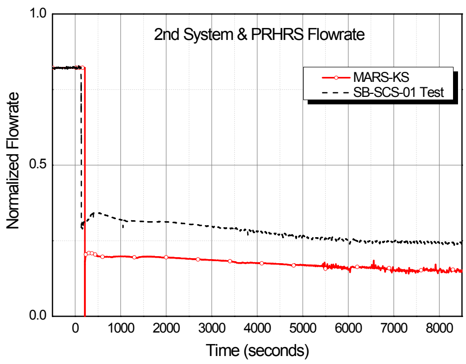

Fig. 8. 2nd System & PRHRS Flowrate

4. Conclusions

An SBLOCA test and its post-test calculation were successfully performed using the SMART-ITL facility and MARS-KS code. The SBLOCA break is a guillotine break, and its location is on the SCS line (nozzle part of the RCP suction).

The steady-state conditions were achieved to satisfy the initial test conditions presented in the test requirement and its boundary conditions were properly simulated. The scenarios of SBLOCA in the SMART design were reproduced well using the SMART-ITL facility and MARS-KS code. The pressures and temperatures of the test and simulation show reasonable behaviors during the SBLOCA test. In general, the simulation results using the MARS-KS code were in good agreement with the test results using the SMART-ITL.

Acknowledgments

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