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Core Cooling Behaviors in SMART-ITL with Passive Safety Injection System and Passive Residual Heat Removal System during a SBLOCA Scenario

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1. Introduction

The Standard Design Approval (SDA) for SMART [1] was certificated in 2012 at the Korea Atomic Energy Research Institute (KAERI). To satisfy the domestic and international needs for nuclear safety improvement after the Fukushima accident, an effort to improve its safety has been studied, and a Passive Safety System (PSS) for SMART has been designed until 2015 [2]. In December 2015, Saudi Arabia and Korea started conducting a three-year project of Pre-Project Engineering (PPE) to prepare a Preliminary Safety Analysis Report (PSAR) and to review the feasibility of constructing SMART reactors in Saudi Arabia.

In addition, an Integral Test Loop for the SMART design (SMART-ITL, or FESTA) [3] has been constructed and it finished its commissioning tests in 2012. Consequently, a set of Design Basis Accident (DBA) scenarios have been simulated using SMART-ITL. Recently, a test program to validate the performance of the SMART PSS was launched and its scaled-down test facility was additionally installed at the existing SMART-ITL facility. [4, 5] Thereafter various kinds of validation tests on SMART PSS have been performed during 2014-2016.

In this paper, the core cooling behaviors were investigated in SMART-ITL with passive safety injection system (PSIS) and passive residual heat removal system (PRHRS) during a SBLOCA scenario.

2. Methods and Results

2.1 SMART and SMART-ITL

SMART is an integral type reactor. A single pressure vessel contains all of the major components, which are the pressurizer, core, steam generator, reactor coolant pump, and so on. SMART-ITL is scaled down using the volume scaling methodology and has all the fluid systems of SMART together with the break system and instruments, as shown in Fig. 1. The height of the individual components is conserved between SMART and SMART-ITL. The flow area and volume are scaled down to 1/49. The ratio of the hydraulic diameter is 1/7. The scaling ratios adopted in SMART-ITL with respect to SMART are summarized in Table 1.

All primary components except for steam generators are equipped in a reactor pressure vessel. However, as the space of the annulus to locate the steam generator is too narrow to install itself inside the SMART-ITL, the steam generator was connected to the hot-leg and cold-leg outside the pressure vessel where the instruments are installed.

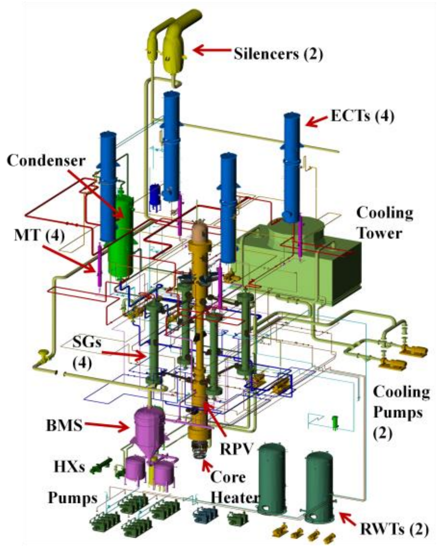

Fig. 1 Schematics of the SMART-ITL.

Table 1 Major Scaling Parameters of the FESTA Facility.

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

SMART is a 330 MW thermal power reactor, and its core exit temperature and pressurizer (PZR) pressure are 323℃ and 15 MPa during normal working conditions, respectively. The maximum power of the core heater in the SMART-ITL is 30% for the ratio of the volume scale. The reactor coolant system of the SMART-ITL was designed to operate under the same condition as SMART.

2.2 SMART Passive Safety System and SMART-ITL implementation

The SMART PSS design is composed of four Core Makeup Tanks (CMTs), four Safety Injection Tanks (SITs), and two-stage Automatic Depressurization

Systems (ADSs) [2]. Individual tanks are connected with the pressure-balanced pipes on the top side and injection pipes on the bottom side. This system is operated when a small break loss of coolant accident (SBLOCA) or the steam line break (SLB) occurs. There are no active pumps on the pipe lines to supply the coolant. This system is only actuated by the passive means of gravity force caused by the height difference because all of the tanks are higher than the injection nozzle around the reactor coolant pumps (RCP).

CMT and SIT were designed based on the volume scale methodology, which is the same methodology used for SMART-ITL. Their heights are conserved, their diameters are scaled down to 1/7, and the area of the tank cross-section is scaled down to 1/49. Detailed scaled values are shown in Table 1.

The SMART-ITL is equipped with four trains of PSIS, 2 stages of ADS and four trains of PRHRS. Each pipe has an isolation valve and a flow meter. The pressure, differential pressure, and temperature can be measured at every pipe and tank. Level and pressure transmitters are installed in each tank.

2.3 Passive Safety System Validation Tests

An experimental facility design for validating the SMART passive safety system was introduced. Through the validation tests, the general thermal-hydraulic performance of the passive safety system can be understood, and the performance of the nozzle geometry of flow distributor, break size and tank geometry can be assessed. Thus, the obtained quantitative data can be applied to a real system design and safety analysis code.

The objectives of this validation tests are to construct a scaled-down test facility, to assess the performance of the CMTs and SITs for SMART, and to analyze the thermal-hydraulic phenomena of flashing, wall film condensation, interfacial direct contact condensation, and thermal stratification expected to occur inside the tank [6-8].

Four trains of PSIS for the SMART design were simulated together with two-stages of ADS and four trains of PRHRS by attaching it to the existing SMART-ITL facility. The tests were performed with single, dual and four trains of PSIS consecutively, but four trains of PRHRS and 2 stages of ADS were already installed.

Table 2 Test Matrix of SMART Passive Safety System Tests.

4-Train Test ID	2-Train Test ID	1-Train Test ID	Break (inch)	Description
F101	T101	S105	2	CMT only
F102	T102	S107	2	SIT only
F103, F103R	T103	S108	2	Reference case
F104	T108	S110	0.4	Break size
F301	-	-	2	Break location @PSV line

Table 2 shows the selected test matrix of single, dual and four trains of PSIS tests for the SMART design. Several kinds of tests were conducted for a SBLOCA scenario to understand the following: 1) the effects of separate CMT and SIT operation, 2) the coupling effect of the CMTs and SITs, 3) the effect of different break sizes of 2 and 0.4 inches, and 4) the effect of break location (SIS line break or PSV line break).

2.4 SBLOCA Scenario of SMART PSS

A SBLOCA scenario was simulated using the SMART-ITL facility. The break type is a guillotine break, and its break location is on the Safety Injection System (SIS) line, which is located at the nozzle part of the RCP discharge, or on the Pressurizer Safety Valve (PSV) line, which is located at the top of pressurizer. The break size is 2 or 0.4 inch in the SMART design.

Table 3 Major Sequence of Events for the SBLOCA Scenario

Event	Trip signal/Set-point
Break	-
LPP set-point	PZR Press = P_{LPP}
Reactor trip signal - Pump coastdown - CMT Act. Signal (CMTAS) - FW stop (F-series)	LPP+1.1 s
Reactor trip-curve start	LPP+1.6 s
MSHP set-point	LPP+4.1 s
CMT injection start	CMTAS+1.1s
PRHR actuation signal	MSHP+1.1 s
PRHRS IV open (Not actuated for S-&T-series)	PRHRAS+5.0 s
FIV close MSIV/ FIV close FW stop (S-&T-series)	PRHRAS+20.0 s (= LPP+25.2 s)
SIT injection signal (SITAS)	PZR Press = P_{SITAS}
SIT injection start	SITAS+1.1s
ADS #1 open	CMT level < $L_{ADS\ \#1}$
ADS #2 open	SIT level < $L_{ADS\ \#2}$
Test end	72 hour or complete injection

The thermal-hydraulic behavior occurs at the same time scale in the SMART-ITL and SMART designs because the SMART-ITL is a full-height test facility. Table 3 shows the major sequence of events for the SBLOCA scenario. The sequence of events are different between S- & T-series and F-series: 1) Feedwater stops earlier in F-series than in S- & T-series; 2) PRHRS is actuated only in F-series.

When a SIS line in the SMART is broken, the primary system pressure decreases with the coolant discharge through the break. When the primary pressure reaches the Low Pressurizer Pressure (LPP) set-point, the reactor trip signal is generated with a 1.1 s delay. Because a turbine trip and LOss of Off-site Power

(LOOP) are assumed to occur consequently after a reactor trip, the feedwater is not supplied and the Reactor Coolant Pump (RCP) begins to coast-down. In addition, a CMT Actuation Signal (CMTAS) is coincidently generated with a reactor trip signal. With an additional 0.5 s delay, the control rod is inserted. When the PRHRS actuation signal is generated by the trip signal of the Main Steam High Pressure (MSHP) 4.1 s after the LPP, the SG secondary side is connected to the PRHRS with a 5 s delay and is isolated from the turbine by the isolation of the main steam and feedwater isolation valves with a 20 s delay. CMT injection starts following the CMTAS with a time delay of 1.1 s by opening the isolation valve installed on the injection line downstream of the CMT.

An SIT Actuation Signal (SITAS) is generated when the RCS pressure reaches below the SITAS setpoint, and the SIT is connected to the RPV with a 1.1 s delay when the isolation valve in the injection line downstream of the CMT is opened. The ADS #1 valve is opened as the CMT level falls below $L_{ADS\ \#1}$ of its full height, and the ADS #2 valve is opened as the SIT level falls below $L_{ADS\ \#2}$ of its full height.

The break nozzle diameter is 2 inches in the SMART design and the scaled-down value is 7.26 mm in the SMART-ITL for a 2.0 inch break. A 0.4 inch break is simulated using an orifice with an inner diameter of 1.45 mm in SMART-ITL.

2.5 Core Cooling Characteristics in SMART-ITL during a SBLOCA scenario

To investigate the core cooling characteristics in SMART-ITL equipped with PSIS, ADS and PRHRS, the F104 test is analyzed together with the S110 and T108 tests.

As shown in Fig. 2, the pressure trends are similar before the injection of CMT. Thereafter it decreases faster in T108 (2 train) than in S110 (1 train) before the actuation of ADS #1. It was estimated that the cooling capacity is higher with dual trains of a PSIS than with a single train of PSIS. ADS #1 is actuated earlier than the injection from SIT during both tests. After the SIT injection, their pressure trends become almost similar. For the SBLOCA test with a 0.4 inch break, the ADS actuation signal occurs earlier than the SIT injection signal and helps the depressurization of RV. This is because the RV is depressurized much slower during the 0.4 inch test than during the 2 inch test. However, the pressure trend in F104 is much faster than those in S110 and T108. It is because the PRHRS is activated. The operation of PRHRS and sufficient safety injection from three trains of PSIS enables the core to be cooled efficiently during the SBLOCA scenario.

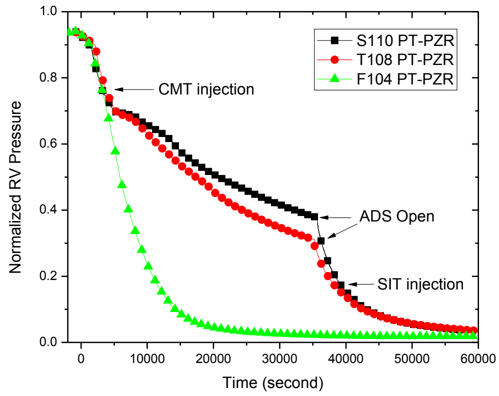

Fig. 2 Comparison of normalized RV pressure

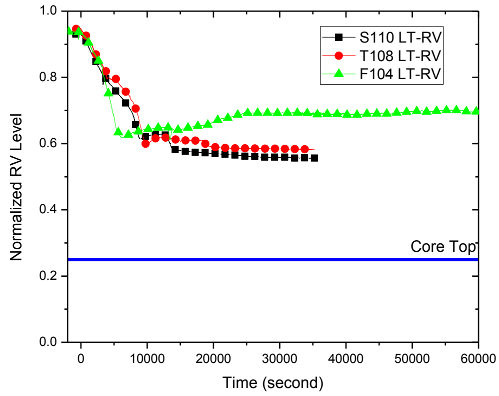

Fig. 3 Comparison of normalized RV water level

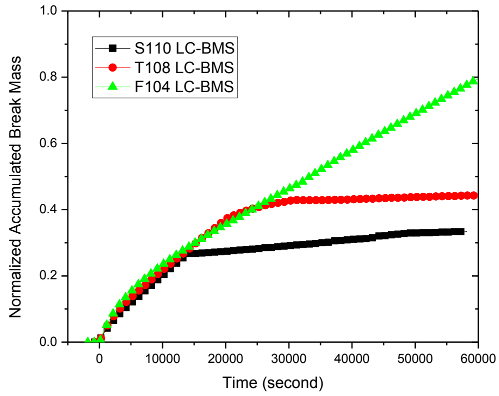

Fig. 4 Comparison of normalized accumulated break mass

As shown in Fig. 3, the RV water level maintains slightly higher during the T108 test than in the S110 test. Multiple trains are operated independently and can increase the RV inventory with the addition of each train. However, the level difference between the single and dual train tests is not very large. After the water level reaches near the safety injection nozzles, the surplus injected water is discharged through the break nozzle. Thus the core is kept to be fully covered during the whole test period. After the opening of the ADS valve, the level transmitter is affected by the discharged flowrate and the test data are not provided as the measured data seem to be uncertain. In F104 the RV level is recovered in an earlier period compared with the single and dual train tests. Fig. 4 shows the accumulated break flowrate measured using a load cell. The accumulated break flow is much larger in T108 than in S110, as expected. The difference starts at around 13,650 seconds. At that point the discharged water is dramatically decreased in the S110 test but continues until 31,920 seconds in the T108. In F104 the accumulated break flowrate increases continuously until 60,000 seconds because water was spilled out of the break.

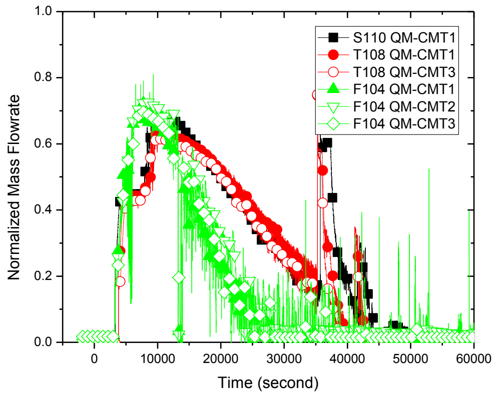

Fig. 5 Comparison of normalized CMT injection flowrate

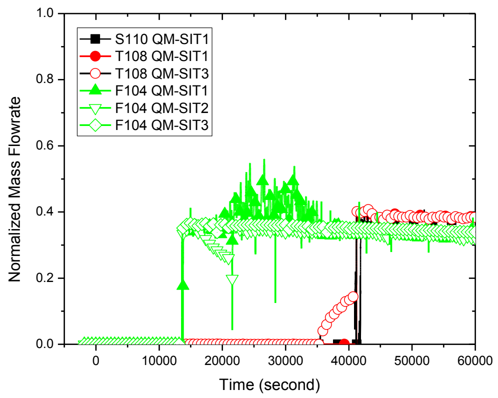

Fig. 6 Comparison of normalized SIT injection flowrate

Figs. 5 and 6 show the injection flow rates of CMT and SIT, respectively. As each train of the CMT and SIT is operated independently, the effect of the train number is negligibly small. The abrupt increase of flowrate at around 35,000 s is due to the opening of ADS #1 during single and dual train tests. The next abrupt increase of flow rate at around 41,000 s is due to the actuation of SIT injection. The CMT flowrate is a little higher in the earlier phase but becomes lower in the later phase in F104 than those in S110 and T108. As the pressure decreases much faster and the SIT actuation signal is actuated earlier in F104, the SIT injection flowrate increases abruptly from around 15,000 seconds. As the pressure decreases much faster and the SIT actuation signal is actuated earlier in F104, the SIT injection flowrate increases abruptly from around 15,000 seconds.

3. Conclusions

In this paper, the core cooling behaviors were investigated in SMART-ITL, which is equipped with PSIS, ADS and PRHRS, during a SBLOCA scenario. The parameters of the RV pressure, RV water level, accumulated break mass, and injection flowrates from the CMT and SIT were compared. Compared with the single and dual train tests, the increased injection rates from three trains of PSIS during the F103 test raised the RV water level in an earlier period, ensuring efficient safety injection and core cooling capabilities.

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