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Experimental Investigation on Thermal-Hydraulic Interaction between CMT and SIT of a Two-Train Passive Safety System during an SBLOCA Test

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1. Introduction

For the last few years, a passive safety injection system(PSIS) of the SMART, integral type reactor[1, 2] has been designed by the Korea Atomic Energy Research Institute (KAERI). Its main function is to maintain the reactor in a safe condition during the design basis accident without any AC power to drive the safety injection pumps and operator action with no more than 72 hours.

The PSIS of the SMART is composed of four trains and two stages of an automatic depressurization system (ADS) additionally. A single train consists of a core makeup tank (CMT), a safety injection tank (SIT).

To verify the design and performance of this SMART passive safety system, two trains of a passive safety were designed and then installed additionally in the existing SMART-ITL facility, an integral test loop of the SMART[3, 4].

This paper describes the test procedure and test result of an SBLOCA simulation to evaluate the performance of a passive safety system consisting of CMT # 1-2, #3, SIT # 1, #3, ADS #1 and ADS #2. The C-type Flow distributors were installed in the upper part of CMTs and SITs.

The initial condition of the transient test is the same as the steady-state operating conditions. The test was carried out according to the sequence of events (SOE) for an SBLOCA scenario.

Most of the thermal-hydraulic properties such as the pressure, temperature, flow rate, and water level showed partially transient phenomenon with the operation of the passive safety system, but the injection characteristics of the CMT and SIT showed good and stable behavior from a macro perspective.

2. Methods and Results

2.1 Overview of SMART-ITL

SMART is a 330 MW thermal power reactor, and its core exit temperature and PZR pressure are 323℃ and 15 MPa during normal working conditions, respectively. The maximum power of the core heater in SMART-ITL (Fig. 1) is 30% for the ratio of the volume scale. The reactor coolant system of SMART-ITL[3,4] was designed to operate under the same conditions as SMART [5].

The reactor coolant pump (RCP) was designed geometrically by the volume scale law, which was applied to the diameter of suction and discharge, and the liquid volume. The scale ratio of the flow rate was in proportion to the related power ratio of the core heater. Four reactor coolant pumps were installed in the upper annulus side of the pressure vessel at an angle of 90 ^{o}.

Four once-through steam generators with a helical coil were installed at the same azimuth as the RCP outside the reactor pressure vessel of SMART-ITL. The steam generator consists of primary and secondary sides. The primary function of the SG is to remove the heat of the RCS. The heat of the primary side is transferred to the secondary side in the steam generator, while the hot reactor coolant is floating through the cell side and the feed water is traveling through the tube side. To simulate the characteristics of the heat transfer, it was designed such that the surface area of the tube was properly scaled down with the scale ratio.

The secondary system consists of a feed water supply system, steam supply system, and condensation and cooling system. It is important to supply the feed water with a constant temperature and to generate the super-heated steam as the boundary values.

The passive residual heat removal system (PRHRS) plays a role in removing the residual heat of the core when an accident that decreases the pressure of the RCS, for example an SBLOCA, occurs. It has four trains. Each train has an emergency coolant tank and heat exchanger for the condensation of the steam. One makeup tank per train was installed for the pressure compensations. Individual components were scaled down by the volume scale ratio, and the pipes were designed for conserving the similarity of the pressure drop.

2.2 Passive Safety System

The passive safety system includes the core makeup tank (CMT) and safety injection tank (SIT). 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 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 gravity force caused by the height difference because all tanks are higher than the injection nozzle around the reactor coolant pumps (RCP).

Fig. 2 shows schematics of one train for the passive safety system of SMART-ITL. Each pipe has an isolation valve and flow meter. The differential pressure and temperature can be measured for every pipe and tank. A level and pressure transmitter is installed in each tank.

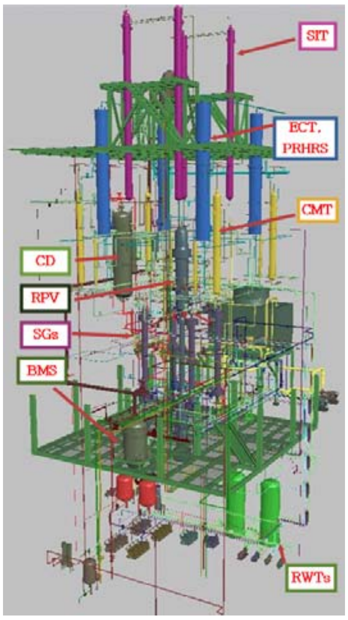

Fig. 1. Schematics of the SMART-ITL.

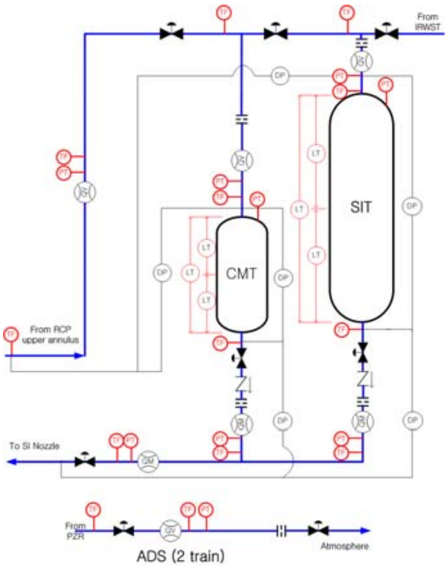

Fig. 2 Schematics of the test facility for SMART passive safety system

The phenomena of flashing and direct contact condensation are expected to occur in the CMT, SIT, and pipes at the early stage. Appropriate thermocouples have to be installed in the pipes and tanks to investigate the complex thermal-hydraulic phenomena after the system is operated by opening the isolation valve.

2.3 Scaling Methodology

CMT and SIT are designed based on the volume scale law of 1/49. Their heights are conserved. The diameter is scaled down to 1/7, and the area of the tank cross-section is scaled to 1/49. The primary scale variables are listed in table I.

Table I: Primary scale variables

Parameters	Scale Ratio	Value
Length, l_{0R}	l_{0R}	1/1
Diameter, d_{0R}	d_{0R}	1/7
Area, a_{0R}	d^2_{0R}	1/49
Volume, V_{0R}	$d^2_{0R}\, l_{0R}$	1/49
Time scale	$l^{1/2}_{0R}$	1/1
Velocity	$l^{1/2}_{0R}$	1/1
Flow rate	$a_{0R}\, l^{1/2}_{0R}$	1/49
Pressure drop	l_{0R}	1/1

Table II: Local scale variables

Parameters	Scale Ratio	Value
Length, l_L	l_L	V_{OR} / k^2
Diameter, d_L	d_L	k
Area, a_L	d^2_L	k^2
Volume, V_L	V_L	V_{OR}
Time scale	$l^{1/2}_L$	$(V_{OR})^{1/2}$ / k
Velocity	$l^{1/2}_L$	$(V_{OR})^{1/2}$ / k
Flow rate	$a_{0R}\, l^{1/2}_{0R}$	k * $(V_{OR})^{1/2}$
Pressure drop	l_L	V_{OR} / k^2

Table III: Description of the steady-state condition

Parameter	Normalized state-state condition (Measurement / Target value, %)
Power	116
PZR pressure	100
1^{st} flowrate	102
SG 1^{st} inlet temperature	100
SG 1^{st} outlet temperature	101
Feed Water. flow rate	100
SG 2^{nd} outlet Pressure	100

To maintain the characteristics of the pressure drop in the pipes between a proto-plant and a facility, a local-phenomena scaling method was applied. The local scale variables are listed in Table II. First, a scale factor, k, for the diameter to satisfy the volume ratio of the pipes was assumed. A length ratio was derived by substituting the factor into the volume scale ratio. Using these two ratios, a temporary k_1 can be selected to satisfy the Friction Number and Orifice Number. Second, another k_2 was selected to satisfy the ratio of the pressure drop, flow rate, and so on. Finally, through the best estimation, a specific k was determined to avoid the distortion of the real phenomena.

2.4 Steady State Condition

Steady-state conditions were applied to satisfy the initial test conditions presented in the test requirement, and its boundary conditions were properly simulated.

A steady-state operation was maintained over 600 seconds prior to the transient test. Table III shows the normalized-major parameters of the target values and test results during the steady-state conditions.

Table IV: Major Sequence of the SBLOCA

Event	Set Point	Time After Break (seconds)
Break		0
LPP set-point	P_{LPP}	718
Reactor trip signal - Pump coastdown - CMT Actuation Signal	LPP+1.1 s	720
Reactor trip-curve start	LPP+1.6 s	721
CMT injection start	LPP+2.2 s	722
PRHR actuation signal PRHRS IV open	LPP+5.2 s LPP+10.2 s	- 728
MSIV / FIV close FW stop	LPP+25.2 s	744 744
SIT injection signal	SITAS:P_{PZR}	-
SIT injection start	SITAS+1.1s	3,729
ADS #1 open	CMT Level	20,947
Stop the test	Complete injection	327,890

The pressure behavior of the primary system is a representative boundary condition because the system trip signal is actuated by the specific pressure value.

Table IV shows the major sequence of events for the transient test as the boundary conditions. When a SIS line was broken, the RCS began to be depressurized. As the pressurizer pressure reached the LPP trip set-point (LPP) at 718 s, the reactor trip was generated about 2 s after the LPP signal. Consequently, the reactor coolant pump started to coast down. The CMT actuation signal was generated. It was shown that a PRHRS actuation signal also occurred. Then the SIT was actuated after the safety injection actuation signal (SIAS). The individual signal was sequentially actuated.

2.5 SBLOCA Simulation of SI Break

A Safety Injection System (SIS) is an important part of a nuclear reactor system during a loss-of-coolant accident. SI lines are connected to the reactor vessel and the makeup water is supplied to itself during the loss-of-coolant accident. During this test, the SBLOCA with a SI line break was simulated.

The break type is a guillotine break, and its break location is on the SI line (nozzle part of the RCP discharge). The thermal-hydraulic behavior happens at the same time in the SMART-ITL and SMART designs according to the time scale ratio. The break nozzle diameter is 50.8 mm in the SMART design and the scaled-down value is 7.26 mm in the SMART-ITL.

An SBLOCA test on the SI line break was carried out according to the sequence of events as follows. The steady-state conditions (constant high pressure and temperature) → break(pressure, temperature, and water level decrease) → LPP → RCP coast down, heater trip (residual heat decay curve) → PRHRS → isolation of the feedwater and steam lines, feedwater stop → CMT actuation → SIT actuation → ADS open.

The constant high pressure and temperature of the primary system under the steady state decreases rapidly after the break starts, as shown in Fig. 3. An individual actuation signal such as the RCP coast down, heater trip, PRHRS, CMT, and SIT worked after the pressure reached a specific value, LPP. The system was cooled down by the safety system from that time. When decreasing the primary pressure, the working time of the CMT, SIT, and ADS were displayed, as shown in Fig. 3 as ①, ②, and ③ respectively. This means that the PSIS pressure vessel cooled down efficiently with the operation of the PSIS, including the CMT, SIT, ADS and PRHRS.

2.6 Injection Characteristics

Fig. 4 shows the flow rate of the CMTs. After opening an isolation valve located on the injection line of the CMT (①), the injection of the core makeup water began. In this initial stage of the CMT injection, steam from the primary system was mixed with the relatively cold coolant at the upper header of the CMT, and thus direct condensation was expected to occur. The initial injection flow rate showed unstable behavior while repeatedly increasing and decreasing.

When the SIT began working, the flow rate was suddenly decreased (②→②') and then increased (②'→②") for a short time as shown in Fig. 5. Before the SIT started working, there was a pressure differences between the primary system and SIT, as shown in ② of Fig. 3. This is the time when the pressure balance takes place. The flow rate from this time (②'→②") was slightly higher than the previous one because this flow rate indicates the sum of the CMT and SIT. This merged flow rate with the CMT and SIT was gradually decreased and efficiently injected. The decreasing slope of the reactor coolant level of the primary system was changed from about 4,000 seconds in Fig. 5, which was the same time as point ②" of Figs. 4 and 5. From this point ②" , i.e., 4,000 seconds, the collapsed level of the primary system was rapidly increased as shown in Fig. 6. Its trends are changed gradually after a sudden little peak in the level when the ADS began working around 21,000 seconds (③). The reactor coolant inventory was sufficiently recovered with a proper operation of safety injection systems.

Fig. 7 shows the temperature results of the inner CMTs. During the initial stage of the CMTs injection, the fluid temperature measured in CMT#1-1 and #3 shows good stratification phenomena. The temperature in the upper side of the CMTs increases rapidly as the steam is injected from the reactor vessel into the CMTs along the saturation temperature. As the surface level is decreased, the surface temperature is also decreased along the saturation temperature corresponding to the CMTs pressure and a lower water temperature is gradually increased. It is estimated that the upper-side CMT#1-1 and #3 are filled with super-heated steam and the inner CMTs are thermally stratified by the inner super-heated steam.

Fig. 8 shows the temperature distribution of the inner SITs. During the initial stage of the SIT injection (②→②") within 4,000 sec, the flow rate of the CMTs decreases and increases a little rapidly. This is the time to increase the temperature of the upper-side SITs to approach the thermal equilibrium between the SIT and primary system. A direct condensation of steam is expected in the upper SITs during this time. After the heat equilibrium, the SIT inner water reaches to a thermal stratification with the different temperatures between its upper and lower side.

3. Conclusions

An SBLOCA test on the SI line break was conducted to evaluate the injection performance between the CMT and SIT of the SMART. The steady state required by the procedure as the initial condition was well maintained. The actuating sequences required by the boundary condition operated on time as well.

- During the initial stage of the SI break simulation, the primary pressure was decreased rapidly and the water of the CMT and SIT was injected well.
- During the initial stage of the CMTs and SITs injection, an unstable injection phenomenon was observed because of a direct condensation of steam with high temperature and pressure.
- An interactive injection between the CMTs and SITs was observed as well. After the injection from two tanks was merged, the injection flow rate became stable.
- During all stages of the CMTs and SITs injection, the coolant was injected efficiently and the decreased collapsed level of the primary system in the early stage was increased appropriately until the end of the simulation.
- The pressure and collapsed level reveals that the RV cooled down efficiently and was sufficiently recovered with a proper operation of the two-train passive safety injection system.

In the near future, a test facility will be equipped with a 4-train passive safety system with a CMT and SIT per train. The co-authors have a plan to carry out new sets of tests using a 4-train passive safety system.

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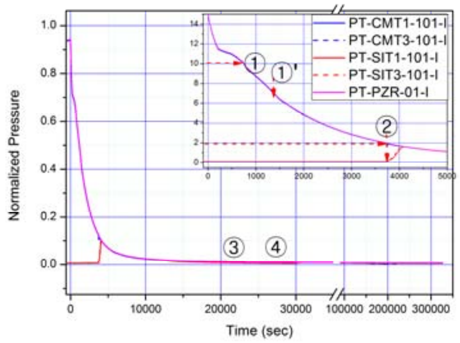
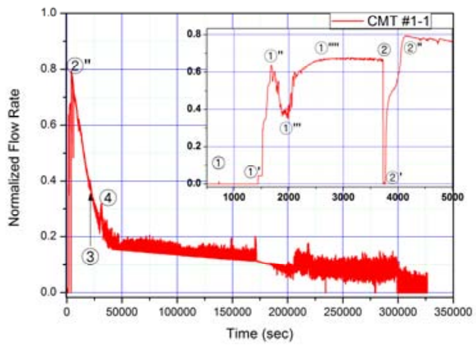
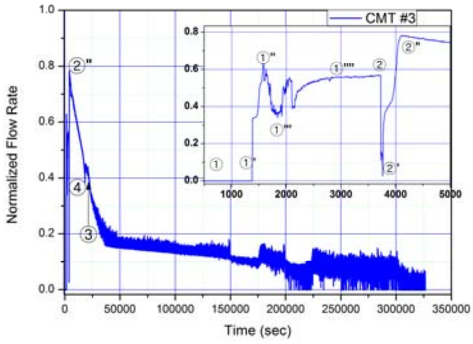


Fig. 3 Pressure of PZR, CMT, and SIT



(a) CMT #1-1



(b) CMT #3

Fig. 4 Injection Flow Rate of CMTs and SITs

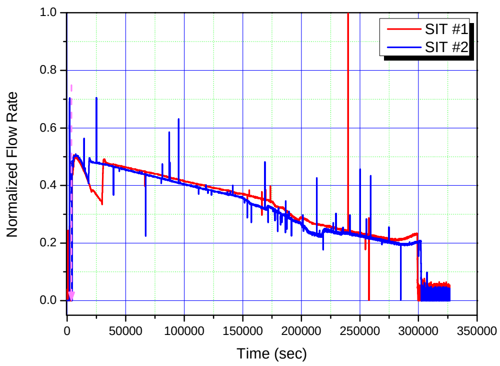


Fig. 5 Injection Flow Rate of SITs

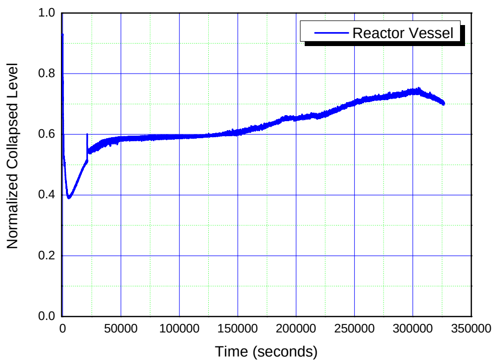
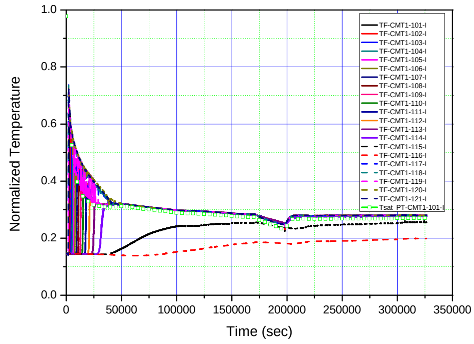
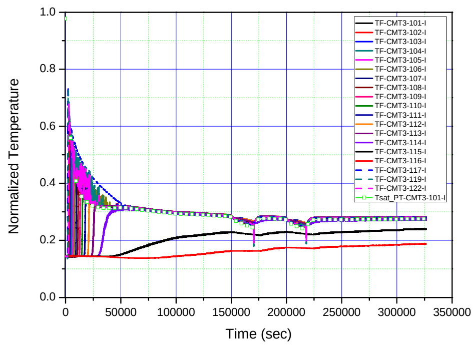


Fig. 6 Collapsed Level of Reactor Coolant System

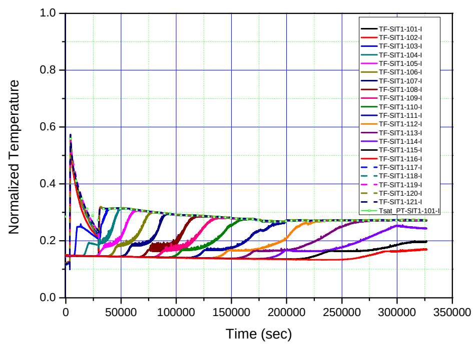


(a) CMT #1-1

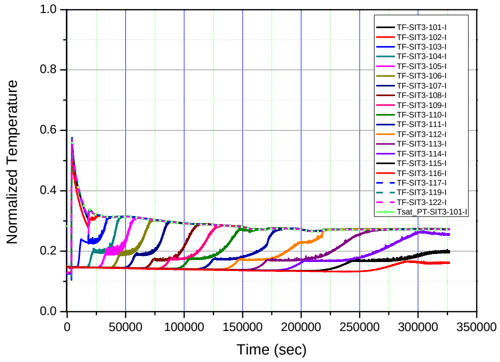


(b) CMT #3

Fig. 7. Temperature distributions of CMTs



(a) SIT #1



(b) SIT #3

Fig. 8. Temperature distributions of SITs