Comparison of CMT Injection Characteristics during Different Test Scenarios using SMART-ITL

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1. Introduction

SMART [1] is an integral type reactor and a single pressure vessel contains all of the major components such as a pressurizer, core, steam generator, and reactor coolant pump. The Standard Design Approval (SDA) for SMART was granted in 2012 by Korea Nuclear Safety and Security Commission. To satisfy the domestic and international needs for nuclear safety improvements after the Fukushima accident, there were a lot of efforts to improve its safety, and a passive safety system (PSS) for SMART was designed in 2015 [2]. It includes four trains of the passive safety injection system (PSIS), two trains of the automatic depressurization systems (ADS), and four trains of the passive residual heat removal system (PRHRS). The SMART PSIS design is composed of four core makeup tanks (CMTs) and four safety injection tanks (SITs). Individual tanks are connected with the pressure balance line (PBL) at the top and the injection line (IL) at the bottom.

In addition, an integral test loop for the SMART design (SMART-ITL) [3] was constructed and it finished its commissioning tests in 2012. Consequently, a set of design basis event (DBE) scenarios was simulated using the SMART-ITL facility. A test program to validate the performance of the SMART PSS was launched in 2013, and its scaled-down test facility was additionally installed at the existing SMART-ITL facility. Various kinds of validation tests on SMART PSS were conducted between 2014 and 2017. In December 2015, Saudi Arabia and Korea started 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 in Saudi Arabia.

To support both the fluid system design and safety analysis groups preparing a PSAR, various validation tests were scheduled to be performed. The validation tests include tests on various safety- and system performance-related event scenarios and on operation procedures for the SMART design. Safety-related event scenarios include seven kinds of scenarios such as feedwater line break (FLB), complete loss of reactor coolant system flowrate (CLOF), uncontrolled control rod assembly (CRA) withdrawal, small-break loss-of-coolant-accident (SBLOCA), steam generator tube rupture (SGTR), total loss of secondary heat removal (TLOSHR), and natural circulation (NC). System performance-related event scenarios are simulated to validate the system performance of PSIS and PRHRS. SMART operation procedure includes the startup operation, power operation, and shutdown operation.

This paper includes the CMT injection characteristics found from tests and data analysis results on the safety-related accident scenarios of SBLOCA, SGTR, and TLOSHR for the SMART design.

2. Methods

2.1 Test Facility

SMART-ITL was designed following a three-level scaling methodology consisting of integral scaling, boundary flow scaling, and local phenomena scaling. The major scale ratios are also summarized in Table 1. 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 2.0 MW, 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, 18.0 MPa and 350 °C. The major components of the SMART-ITL facility include a primary system, secondary system, PRHRS, auxiliary system, safety injection system, break system, and break measuring system. Fig. 1 shows a schematic of the SMART-ITL facility.

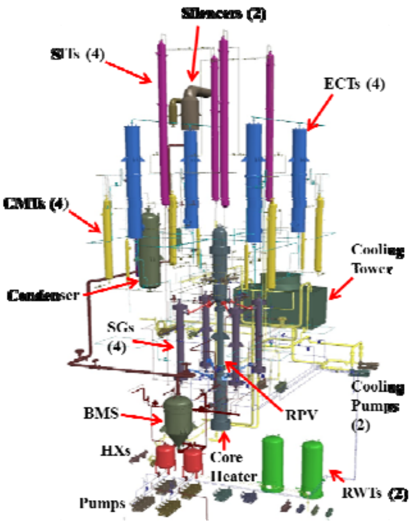

Fig. 1 Schematic diagram of SMART-ITL facility

SMART-ITL is equipped with four trains of the PSIS. The SMART PSIS design is composed of four CMTs, four SITs and four PBLs, four ILs and related pipes [2]. Individual tanks are connected with the PBLs at the top and the ILs at the bottom. This system is operated when an SBLOCA, SGTR or TLOSHR occurs. There are no active pumps in 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 located higher than the injection nozzle around the reactor coolant pumps (RCPs). The schematic diagram of the PSIS is shown in Fig. 2. The CMT and SIT were scaled down based on the volume scale methodology used for SMART-ITL.

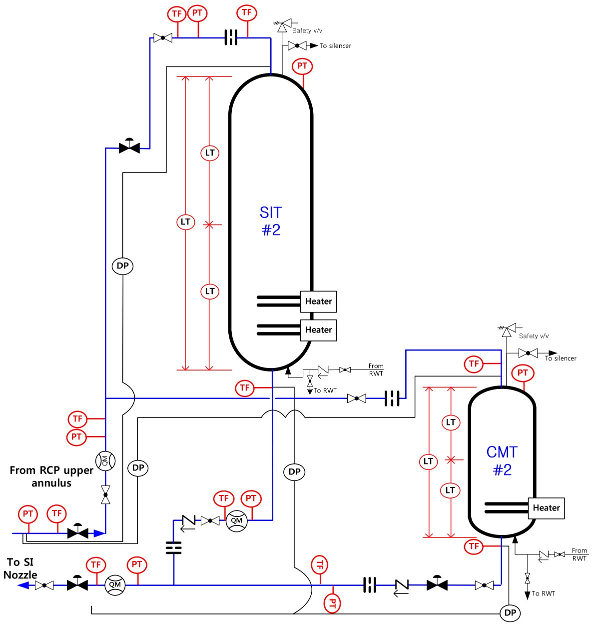

Fig. 2. Schematic diagram of PSIS

2.2 Types of Accidents

Safety related design bases events (SRDBEs) of the SMART are listed as below excluding the reactor building design bases events (RBDBEs).

1) Increase in heat removal by the secondary system
2) Decrease in heat removal by the secondary system
3) Decrease in reactor coolant flow rate
4) Reactivity and power distribution anomalies
5) Increase in the reactor coolant inventory
6) Decrease in the reactor coolant inventory
7) Radioactive release from a subsystem or components

Since SMART has a particular design and operational characteristics of an integral type reactor, it has events similar to as well as different from those of the conventional loop type PWR plants. Each postulated initiating event can be classified into one of the above general categories depending on resulting effects on SMART plant after such an event occurs according to reference [4].

Each of DBEs is able to be classified into several categories by the qualitative or quantitative method. Various classification methods of initiating events are summarized in several categories that the event classification based on the event frequency is made by various criteria and USNRC adopts the event classification method based on the qualitative criteria. The interesting events in the viewpoint of the thermal hydraulics are the situation that the RCS inventory is reduced and the core uncover is concerned, the pressure barrier that physically isolates the RCS from the secondary system is damaged or broken, and the RCS is pressurized due to the loss of secondary heat removal source. The representative events are SBLOCA, SGTR, and TLOSHR.

An SBLOCA is the representative and most severe design basis event (DBE) in the SMART and initiated by the break of passive safety injection line (SIL) or pressurizer safety valve (PSV) line. The inventory and pressure of the reactor coolant system (RCS) are discharged through the break and depressurized, respectively. In the test, the break type is a guillotine break, and its break location is on the injection line of the passive safety injection system (PSIS), which is connected to the nozzle part of the RCP discharge, or on the PSV line, which is located at the top of the pressurizer. The break sizes are 2 or 0.4 inches in the SMART design.

An SGTR is a postulated accident, where one tube inside a steam generator (SG) is ruptured. The helical tubes inside SG isolate the secondary system from the reactor coolant system, preventing leakage of radioactive materials toward the environment. The rupture of pressure boundary between the reactor coolant and the secondary system is an important accident in view of the radioactive material release. However, in the thermal hydraulic view, the pressure balance between the RCS and the train of secondary side which the tube is ruptured, the residual heat removal from the RCS to the PRHRS, and the supplementation of the RCS inventory from the PSIS are more important phenomena.

A TLOSHR accident is a beyond design basis event (BDBE) resulting from a hypothetical loss of main feedwater and emergency feedwater to steam generators (SGs). Feedwater supplied to SGs is completely and instantaneously terminated as the TLOSHR accident begins. Furthermore all alternative feedwater provided by the PRHRS is not available for the entire duration of the TLOSHR accident. The complete loss of all feedwater to SGs can be caused by common failures of pump function and/or valve misalignment in the feedwater system. The design purpose of PRHRS is to deliver emergency feedwater to SGs for removing a decay heat in the core. However, it is conservatively assumed that the feedwater and PRHRS are unavailable during TLOSHR accident due to unknown failure.

3. Comparison of Passive Safety Injection Characteristics

Passive injection typically reaches a stable injection condition with 3-step phase changes. This procedure indicates the recirculation phase (①→①', A. single-phase water), oscillating phase (①'→①'', B. two-phase mixture of steam and water) and injection phase (after ①'', C. single-phase steam). This change of phase is related to the fluid state of the PBL. In the recirculation phase, liquid coolant from reactor pressure vessel (RPV) is transported to the CMT along the PBL. In the oscillating phase, mixture with the liquid and vapor, and in the injection phase, the vapor does, respectively. The injection flow rate reaches the peak value after vapor transport in the PBL. The change of phase in the PBL can be inferred from the fluid temperature change inside the PBL and CMT and from the CMT water level change.

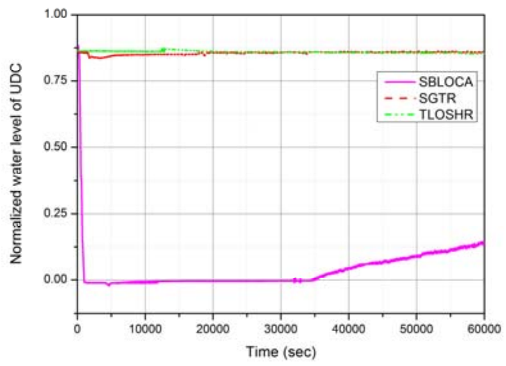

Fig. 3. Water level of UDC for SBLOCA, SGTR, and TLOSHR.

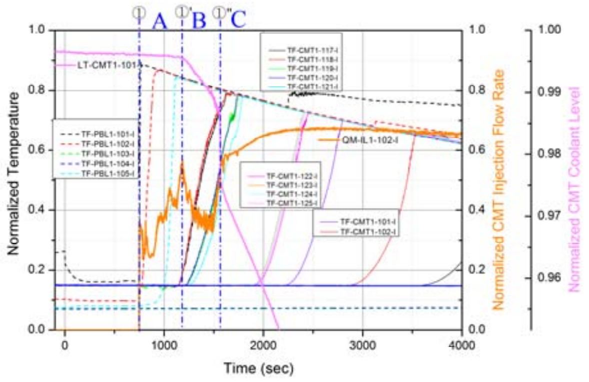

Fig. 4. Fluid temperature of CMT and PBL, and water level and injection flow rate of CMT for SBLOCA.

Fig. 3 shows the water level of upper down-comer (UDC) corresponding to the RCP discharge region of the RPV for the different accident tests such as the SBLOCA, SGTR, and TLOSHR. The upper part of the UDC is the starting point of the PBL and the same elevation of the RCP is the ending point of the IL. In the SBLOCA test, the UDC level is suddenly decreased due to the blow down through the broken safety injection line (SIL) even though the CMT coolant is injected from the other SILs. On the other hand, in the test of the SGTR and TLOSHR, the level maintains the full height during the tests.

Figs. 4 through 6 show the temperatures of the CMT and PBL, as well as the water level and injection flow rate of the CMT.

Fig. 4 shows the major parameters measured in the SBLOCA test. In the SBLOCA accident simulation test in which one SIL is broken out of four SILs, the RCS coolant is blow-down to the outside, so the depressurization and the reduction of the RCS inventory occur at the same time. Since the SIL is connected to the UDC of the RPV where the RCP is installed, the water level of the UDC decreases sharply after the accident. Then, when the CMT starts to operate, the fluid inside the PBL begins to move in the CMT direction in a single-phase liquid state. This corresponds to the beginning of the recirculation phase. At the same time, the UDC coolant begins to flow into the PBL, and the internal temperature of the PBL begins to rise. As the temperature of the PBL becomes equal to the RCS temperature, the fluid temperature of the CMT top region begins to rise. Since there is no change in the CMT water level up to this point, it can be seen that the liquid fluid has flowed into the CMT. However, since the temperature of the CMT upper region starts to rise, the water level of the CMT starts to decrease gradually, and the rising injection flow starts to decrease gradually. It can be seen that the oscillating phase started when the gas and liquid fluid flowed into the CMT through the PBL. When the temperature at the top of the CMT is approximately equal to the internal temperature of the PBL, the CMT injection flow begins to rise sharply, and the CMT level drops slightly but decreases sharply. From this point on, the injection flow starts to show stable behavior, and the water level starts to decrease at constant slope. In this time, injection phase starts.

The behavior of the 3-step phase change is confirmed in SGTR and TLOSHR, but the phase change periods are different from each other.

SGTR shows that when the coolant of the RCS passes through the SG tube to the steam pipe and the PRHRS operation is started, the steam pipe and the feed pipe are completely isolated, the RCS coolant is moved into the PRHRS, and the both pressures of PRHRS connected to the steam generator secondary side and the RCS is equalized. That is, it can be seen as a kind of LOCA before PRHRS is activated. The pressure and inventory of RCS is reduced by a certain amount. However, since the UDC water level is higher than that of SBLOCA, the recirculation phase and oscillating phase are maintained longer than SBLOCA as shown in Fig. 5.

In TLOSHR, the RCS pressure is increased due to the loss of heat removal by the secondary system at the beginning of the accident. However, as the reactor trip signal is generated due to the high pressure of the pressurizer, the RCS is started to be depressurized and the volume of RCS is reduced.

Because the CMT operates to compensate for the reduction in the volume of the reactor coolant, the UDC water level declines moderately compared to the accidental reduction of the reactor coolant inventory due to the reactor coolant being released by the break. In the Fig. 6, the recirculation phase is maintained for about 60,000 seconds. The CMT injection flow rate decreased with time and the internal fluid of the CMT was stratified, but it did not rise to the PBL fluid temperature and the CMT water level was maintained. The PBL and CMT upper temperatures became the same, the water level dropped slightly, and the oscillating phase where the injection flow rises again was maintained for a very short time. The CMT internal temperature gradually began to equal PBL, and the injection phase started as the CMT water level began to decrease at a constant slope.

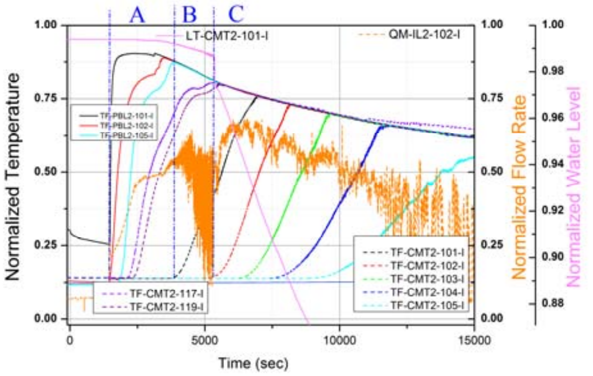

Fig. 5. Fluid temperature of CMT and PBL, and water level and injection flow rate of CMT for SGTR.

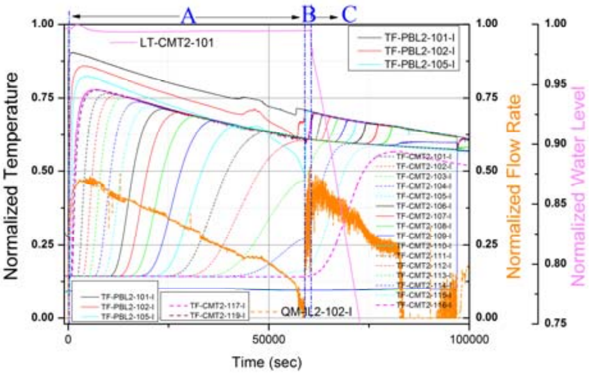

Fig. 6. Fluid temperature of CMT and PBL, and water level and injection flow rate of CMT for TLOSHR.

According to the characteristics of the accident, the level of UDC connected PBL showed different distribution. It was also confirmed that phase change of PBL was affected by this distribution. However, this is not a change in the recirculation-oscillating-injection phase itself, which is a characteristic of the phase change, which appears to be the difference between the time when the phase change appears and the time distribution maintained.

4. Conclusions

Three different tests such as the SBLOCA, SGTR and TLOSHR were carried out using SMART-ITL with PSIS. The depressurization of RCS and loss of RCS inventory for the SBLOCA and SGTR, and pressurization and volume reduction of reactor coolant for TLOSHR are specific characteristics of these tests. The PSIS was operated in the individual tests and 3-step phase changes such as the liquid, mixture, and vapor was commonly observed. However, the times each phase change appeared and maintained were different case by case. The water level of the UDC, which is the RCP discharge region and the PBL connection location as well, took an important role in each phase change. Each phase change was begun according to the water level of the UDC.

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REFERENCES

[1] K. K. Kim et al., SMART: The First Licensed Advanced Integral Reactor, Journal of Energy and Power Engineering, vol.8, p.94, 2014.
[2] Y. M. Bae, “Report of Passive Safety System,” SER-410-FS403-SD, KAERI Internal Report, 2012.
[3] H. S. Park, S. J. Yi, C. H. Song, SMR Accident Simulation in Experimental Test Loop, Nuclear Engineering Int., p12-15, November 2013.
[4] USNRC, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants, LWR Edition," Regulatory Guide 1.70, Rev. 3, U.S. Nuclear Regulatory Commission, November, 1978.