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Comparison of Natural Circulation Test Results with SMART-ITL: CLOF and FBL

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1. Introduction

SMART, one of small modular reactors (SMRs) is an integral type reactor which was developed by Korea Atomic Energy Research Institute (KAERI) [1]. Major components, i.e., a steam pressurizer (PZR), core, steam generator (SG), and reactor coolant pump (RCP) are located in a single reactor pressure vessel (RPV). SMART-ITL [2] was constructed for thermal-hydraulic integral effect tests and several types of integral tests were simulated with 4 trains of passive safety systems (PSSs); design basis accidents (DBA), safety related (SR) tests, system performance (SP) tests, operation and maintenance (OM) tests and so on.

A complete loss of reactor coolant flow rate (CLOF) and a feed line break (FLB) are safety related accident scenarios which assume a non-loss-of-coolant-accident (non-LOCA) of RCS. These scenarios were simulated with SMART-ITL and the both CLOF and FLB tests used a passive residual heat removal system (PRHRS), which is one of passive safety systems in the SMART. In this paper, performance of PRHRS will be compared according to two different natural circulation tests.

2. Experimental Facility and Test Scenarios

2.1 SMART-ITL

Fig. 1 shows components of SMART-ITL which were designed to maintain a natural circulation effect with prototypical height and 1/49 scaled area and volume. It followed a three-level scaling method of Ishii and Kataoka [3]. The scaling ratios of SMART-ITL are summarized in Table I [4]. The maximum core power with electric heaters is 2.0 MW and it is about 30% of the scaled full power. The design pressure and temperature of SMART-ITL are 18.0 MPa and 350℃. The major components of the SMART-ITL consist of a reactor coolant system (RCS), 4 trains of RCP, SG, secondary system, PRHRS and passive safety injection system (PSIS). There are also an auxiliary system, a break simulation system, and a break measuring system.

2.2 PRHRS of SMART-ITL

Purpose of the PRHRS is to prevent over-heating and over-pressurizing of the RCS in the SMART. The SMART-ITL also installed the PRHRS to satisfy the purpose. When an accident occurs, decay heat from core is transferred to the secondary system through SG. The PRHRS uses the main steam (MS) lines and main feedwater (MF) lines for two-phase natural circulation loop. There are four trains in the test facility and each train is composed of an emergency cooldown tank (ECT), PRHRS heat exchanger (PHX), PRHRS makeup tank (PMT), valves, and pipes as shown in Fig. 2 [4]. When the PRHRS actuation signal is activated, the two-phase natural circulation loop is immediately triggered to start opening the bypass valves, which connect to the secondary system. Then, the steam from the MS lines is injected into the PHX submerged in the ECT, and the condensed water is returned to the MF lines to cool down the primary system through steam generators. The PRHRS was designed to reduce the coolant temperature under the shutdown cooling initiation temperature within 36 h after an accident and to maintain it for at least another 36 h.

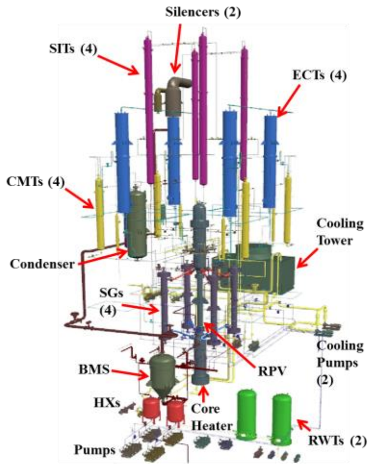

Fig. 1. Components of SMART-ITL

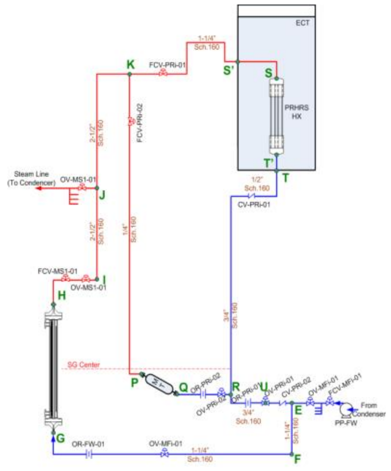

Fig. 2. Schematic of PRHRS in SMART-ITL [4]

Table I: Scaling ratios of SMART-ITL [4]

Parameters	Scale Ratio	SMART-ITL
Length	l_{0R}	1/1
Diameter	d_{0R}	1/7
Area	d_{0R}^2	1/49
Volume	$d_{0R}^2 \cdot l_{0R}$	1/49
Time scale	$l_{0R}^{1/2}$	1/1
Velocity	$l_{0R}^{1/2}$	1/1
Flow rate	$a_{0R} \cdot l_{0R}^{1/2}$	1/49

2.3 CLOF vs. FLB

A complete loss of reactor coolant flow rate (CLOF) is a non-LOCA scenario without flow rate driven by RCPs. When a CLOF event occurs, the forced convection of the coolant is not sustained and the reactor coolant flow rate rapidly decreases since all RCPs fail simultaneously. The departure from nucleate boiling ratio (DNBR) rapidly decreases because of the decreased coolant flow while the control rod assemblies (CRAs) are inserted into the core after the reactor trip signal is activated. A partial loss of reactor coolant flow event occurs when some RCPs fail. Hence, the decrease in the coolant flow is not as severe as that of a CLOF event since intact pumps are still operational until the reactor trip.

Table II shows the sequence of events for the CLOF tests with SMART-ITL. A CLOF accident is an anticipated operational occurrence, which causes a complete loss of primary flow rate by the initiation of the RCP coast-down owing to the failure of the electrical power supply to the RCP. The feedwater pump and turbine also stop due to the loss of electricity. In this case, the core outlet temperature could increase rapidly due to the RCP coast-down, and the PZR pressure would then increase with the volume expansion of the RCS inventory. When the PZR pressure reaches the high pressurizer pressure (HPP) trip set-point, the reactor trip signal is generated with a 1.1 second delay. However, since the SMART-ITL is operated in 20% of full power of SMART, the HPP condition cannot be reached. In this event scenario, we selected an alternative reactor trip signal generated by the low RCP speed. The RPS is activated when the RCP speed decreases down to 90% of normal value at 0.37 seconds. As a result, the reactor trip occurs after the RCP stop with 0.37 s + 1.1 s delay. At the same time, the PRHRS actuation signal (PRHRAS) and CMT actuation signal (CMTAS) are generated by the low feedwater flow rate. Also the SGs are started to be isolated from the turbine by the main steam isolation valves (MSIVs) and feedwater isolation valves (FIVs), and are then connected to the PRHRS. After an additional 0.5 second delay, the control rod is inserted. When RCP trip + 2.2 s (CMTAS + 1.1 s), the 4 trains of CMT injection start. After 6.1 s from RCP trip (PRHRAS + 5.0 s), MSIV/FIV closing and PRHRS isolation valve opening are completed. After the operation initiation of PRHRS, a two-phase natural circulation occurs inside the PRHRS. The decay heat generated from the core is transferred through the SGs, and it is removed by the PRHRS heat exchangers, located in an ECT. If the temperature of RCS reaches to safety shut down temperature, 215 ℃, the test can be finished.

Table II: Sequence of Event for CLOF Experiment

Event	Trip signal and set-point
Event occurs	RCP stop & RCP coast-down FW pump stop Turbine stop
Arrival of RCS trip set-point by low RCP speed	RPM = 0.9×RPM$_{normal}$ RCP stop + 0.37 sec
Actuation of RCS trip signal - Actuation of CMTAS - Actuation of PRHRAS - MSIV/FIV close start - PRHRS IV open start	Reactor protection signal (RPS) + 1.1 sec
Control rod injection	RPS + 1.6 sec (RCS trip signal + 0.5 sec)
4 trains of CMT injection	RPS + 2.55 sec (CMTAS + 1.45 sec)
MSIV/FIV close completed PRHRS IV open completed	RPS + 6.1 sec (PRHRAS + 5.0 sec)
End of event	36 hrs. after PRHRS operation (RCS Temp. < 215 ℃)

The feed line break (FLB) accident is initiated by partial or total rupture of a feedwater line located inside or outside a reactor building.

Table III shows the sequence of events for the FLB tests with SMART-ITL. Once feedwater line rupture occurs, coolant inside the secondary loop is discharged rapidly. Consequently, the flow rate of the feedwater line as well as the secondary system is decreased and the heat transfer rate through SG decreases. As a result, the temperature inside the primary loop and the pressurizer pressure increase. After elapse of dozens of seconds, the set point for the HPP, 16.53 MPa is reached. This is the reactor trip set point. After 1.1 second delay time, the reactor trip signal is generated and turbines are stopped, and reactor coolant pumps start to coast-down. At the same time, PRHRAS is generated by the low feedwater flow rate, and CMTAS is generated. The control rod insertion starts 0.5 seconds after the reactor trip signal (HPP + 1.6 seconds). The reactor coolant system reaches the maximum pressure (17.27 MPa) and the pressurizer safety valve is opened. The CMT injection starts 1.45 seconds after the reactor trip signal. The PRHRS isolation valves are fully opened 5 seconds (HPP + 6.1 seconds) after the PRHRAS. At the same time, the FIV and the MSIV are fully closed. PRHRS starts to operate with natural circulation that involves SGs and PRHRS heat exchangers in ECT. The reactor is cooled down gradually through the PRHRS heat exchangers. The PZR safety valve is closed when the PZR pressure drops to 13.87 MPa. The event is terminated as the safe shutdown condition is reached: the reactor coolant temperature less than 215 ℃ within 36 hours.

Table III: Sequence of Event for FLB Experiment

Event	Trip signal and set-point
Initiation of break - Isolation of break SG train - Loss of feedwater	BREAK
Arrival of RCS trip set-point by high pressure of PZR	HPP (Pressure of PZR= 16.53 MPa)
Actuation of RCS trip signal - Turbine trip - RCP coast-down - Actuation of CMTAS - Actuation of PRHRAS - MSIV/FIV close start - PRHRS IV open start	Reactor protection signal (RPS) + 1.1 sec
PSV opening	Pressure of PZR = 17.27 MPa
Control rod injection	RPS + 1.6 sec (RCS trip signal + 0.5 sec)
4 trains of CMT injection	RPS + 2.55 sec (CMTAS + 1.45 sec)
MSIV/FIV close completed PRHRS IV open completed	RPS + 6.1 sec (PRHRAS + 5.0 sec)
PSV closure	Pressure of PZR = 13.87 MPa
End of event	36 hrs. after PRHRS operation (RCS Temp. < 215 ℃)

3. Comparison Results

3.1 Pressure of PZR

Fig. 3 shows the comparison of PZR pressure trend. The pressure of CLOF stared to decrease after reactor trip set-point in 1 second after RCP stop. The pressure of FLB reached the reactor trip set-point, 16.53 MPa after 109 seconds. The different maximum pressure was due to the different sequence of event. The difference of pressure was maintained until around 80,000 seconds.

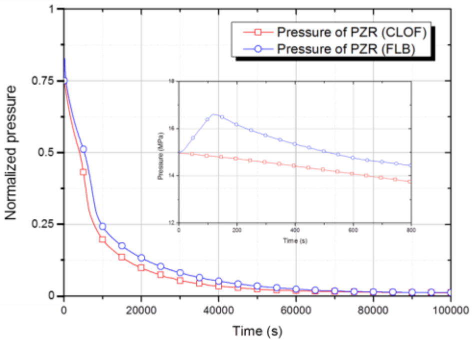

Fig. 3. Comparison of PZR pressure

3.2 Mass flow rate of RCS

Fig. 4 presents the comparison of RCS mass flow rate trend. After reactor trip, the RCS flow mode turned from a forced flow to a single-phase natural circulation in both CLOF and FLB. The natural circulation was maintained until the end of test. In order for the flow to be sustained at a certain level, temperature difference should be maintained. It is estimated that the PRHR operation and the cold water injection from CMTs enabled that difference. The RCS mass flow rate of CLOF was slightly larger than the one of FLB. The mass maximum mass flow rate of CLOF was about 9% greater than the one of FLB. After 80,000 seconds, the two values also became similar.

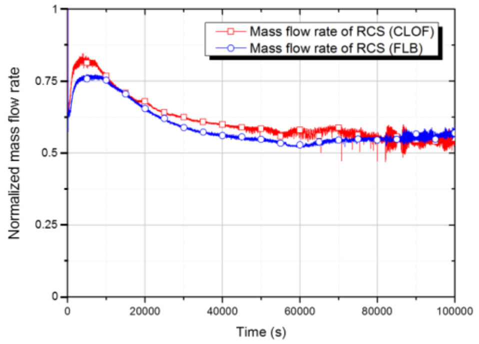

Fig. 4. Comparison of RCS flow rate

3.3 Mass flow rate of PRHRS

Fig. 5 shows the comparison of PRHRS mass flow rate trend. After reactor trip, the secondary system was switched to PRHRS. The flow mode also turned from a forced flow to a two-phase natural circulation in both CLOF and FLB. The PRHRS mass flow rate of CLOF was larger than the one of FLB until 17,000 seconds. After that the PRHRS mass flow rate of CLOF was slightly less than the one of FLB. The maximum mass flow rate of CLOF was about 31% greater than the one of FLB. It means the PRHRS mass flow rate of CLOF was about three times larger than one of FLB. It was because that one train of PRHRS in the FLB was not operated due to break on the feedwater line #1. The natural circulation was maintained around 60,000 seconds in the CLOF and 80,000 seconds in the FLB.

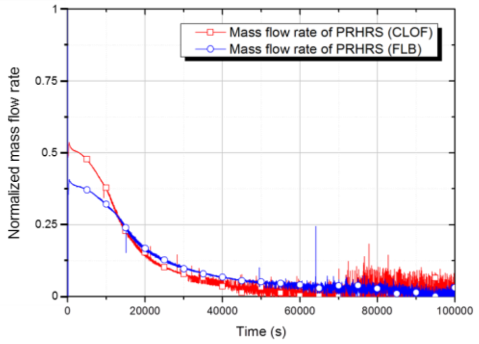

Fig. 5. Comparison of PRHRS flow rate

3.4 Temperatures of ECT

Fig. 6 shows the comparison of ECT #2 temperature. The fluid temperature of middle of ECT increased first. And the fluid temperature of top of ECT increased with about 1,000 seconds delay and the fluid temperature of bottom of ECT was slowly increased. Since the initial temperatures of ECT were set to the atmosphere temperature, there were difference between CLOF and FLB. However, the trends of fluid temperature increase are similar except for the one in case with CLOF (the fluid temperature of bottom of ECT). The others reached saturation temperature after 40,000 seconds, but the fluid temperature of bottom of ECT in case with CLOF was maintained in the subcooled condition.

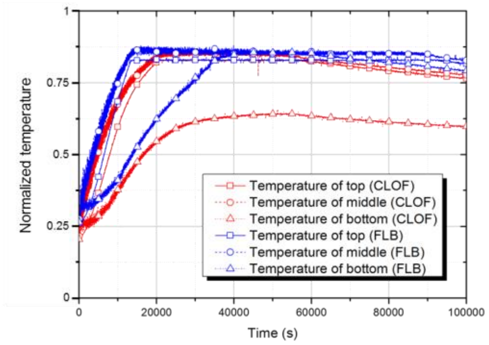

Fig. 6. Comparison of ECT temperatures

3.5 Water level of PRHRS heat exchanger and ECT

Fig. 7 shows the comparison of PRHRS water level of PHX and ECT. The trends of PRHRS water level were similar in both CLOF and FLB tests. The water level of PHX decreased after PRHRS operation and it reached bottom around 10,000 seconds. And the water level was stared to be recovered after PRHRS stop (after 60,000 seconds in CLOF & after 95,000 seconds in FLB). The water level of ECT increased slightly until the fluid temperature of top of ECT reached the saturation temperature. The sensible heat increased the ECT temperature and the expansion of water volume was presented as water level increase until that. After that the water level of ECT stared to decrease due to boiling.

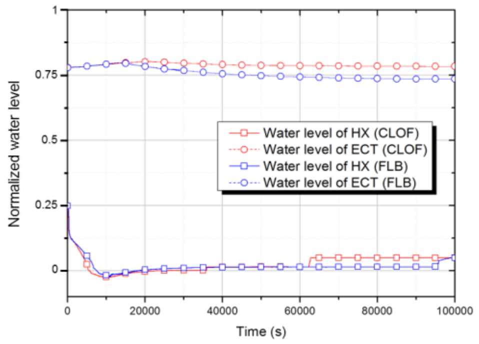

Fig. 7. Comparison of PRHRS water level (PHX and ECT)

3. Conclusions

The safety related scenarios assuming non-LOCA of RCS, CLOF and FLB tests were carried out with SMART-ITL in the KAERI. The representative trends of natural circulations both in the RCS and in the PRHRS were investigated together. Although the natural circulation flow rates of the RCS and PRHRS were different depending on the number of PRHRS train (4 trains in CLOF and 3 trains in FLB), but the characteristics of each train's operation are independent.

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