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Experimental Study of Natural Circulation in Complete Loss of Coolant Flow Accident with SMART-ITL

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) is conducting an experimental study using SMART-ITL to test the performance of SMART, a small modular reactor (SMR) that had been developed and obtained a standard design license from domestic technology [1]. Among the various design basis accidents (DBA), a complete loss of reactor coolant flow (CLOF) is caused by the simultaneous shutdown of the four reactor coolant pumps (RCP) operating at high speeds due to the loss of power to all reactor coolant pumps unexpectedly during normal operation. The forced circulation flow is completely lost. At this time, the core coolant temperature rises as the reactor coolant flow rate decreases. Even the core output decreases due to the reactivity feedback effect due to the rise of the coolant temperature and the insertion of the control rod assembly, but the temperature and pressure of reactor coolant system (RCS) continue to increase because the heat removal amount from the core is decreased due to the loss of forced flow rate. When the RPM of the reactor coolant pump reaches the reactor coolant pump low speed set point or the pressure reaches pressurizer high pressure set point, the reactor is shut down. When the reactor shut downs and the feed water flow of the secondary system decreases, the steam generators are isolated from the turbine and connected to Passive Residual Heat Removal System (PRHRS). The PRHRS is passive safety system (PSS) of SMART for removing the decay heat from the reactor core using an emergency cooling tank (ECT) and internal heat exchanger. Then, the decay heat generated in the reactor core is removed by two-phase natural circulation in the PRHRS. In this study, we can compare and evaluate the effect of heat transfer between two-phase natural circulation in the PRHRS and single-phase natural circulation in the primary system after reactor shutdown.

2. Experiment for CLOF Accident

In this section brief introduction of SMART-ITL with PRHRS, steady-state experiment, sequence of events, and transient simulation of CLOF are described.

2.1 SMART-ITL with PRHRS

The SMART acquired a standard design license with 330 MWth power, but it increased up to 365 MWth in SMART pre-project engineering (PPE) for request from Saudi Arabia. The SMART-ITL, which is an integral test loop with 1/49 scale ratio of area and volume from SMART, has an electric heated core of 2 MW as the maximum power [2]. It is design condition of SMART-ITL and is also about 27% of operation condition in SMART. The decay heat can be simulated from a reduced core heat and the anticipated distortion from the initial condition due to difference of core heat is ignored.

The SMART-ITL has 4 trains of PRHRS as shown in Fig. 1 [3]. The PRHRS, which is connected with steam generators, plays as roles to not only remove the decay heat of the primary system with two-phase natural circulation but also maintain coolant temperature under safety shut down temperature, 215 ℃, for 36 hrs after accident.

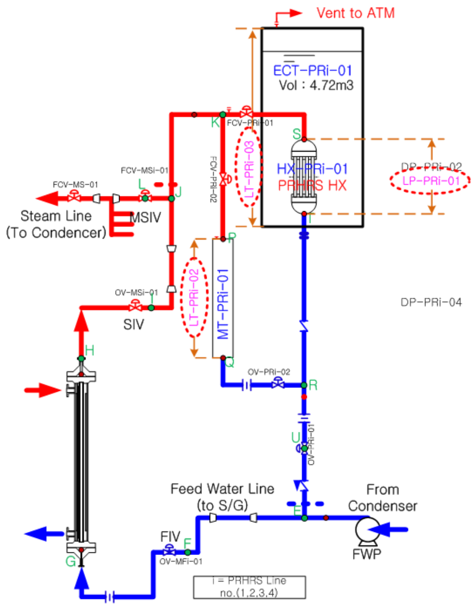

Fig. 1. PRHRS of SMART-ITL [2]

2.2 Steady-state Experiment

Table I presents steady-state condition of 20% core power. The increased core power was applied including heat loss. The core exit temperature and PZR pressure were 320.6 ℃ and 15.05 MPa. The mass flow rates were 10.26 kg/s for primary system and 0.769 kg/s for secondary system which were maintained by electric pumps. The steady-state was operated during 1,450 s before the simulation of CLOF.

Table I: Steady-state Condition of 20% Core Power

Parameter	Target Value	Measured Value
Core Power (MW)	1.50	1.67 (Heat Loss 0.17)
Core Coolant Temp. (In / Out) (℃)	295.5 / 320.9	295.5 / 320.6
S/G Coolant Temp. (In / Out) (℃)	320.9 / 295.5	320.6 / 298.1
Mass Flow Rate of 1ry Coolant, kg/s	10.23	10.26
Pressure of PZR, MPa	15.00	15.05
Coolant Temp. of PZR, (℃)	342.1	342.1
Volume of Coolant in PZR, % (m)	70 (3.12)	70.6 (3.14)
Core Decay Heat	ANS-73 × 1.2	ANS-73 × 1.2
Feed Water / Main Steam Temp., (℃)	230.0 / 302.3	230.2 / 314.7
Mass Flow Rate of 2ry Coolant, kg/s	0.778	0.769
Feed Water / Main Steam Pressure, MPa	6.71 / 5.62	5.71 / 5.62

2.3 Sequence of Events

Table II shows the sequence of events for the CLOF scenario of the SMART design. 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 feed water 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 pressurizer pressure would then increase with the volume expansion of the RCS inventory. When the pressurizer 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 PRHRAS and CMTAS are generated by the low feed water flow rate. Also the SGs are started to be isolated from the turbine by the main steam and feed water isolation valves, 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. With the operation of PRHRS, a two-phase natural circulation occurs inside the PRHRS loop. The decay heat generated from the reactor core is transferred through the SGs, and it is eventually removed by the PRHRS heat exchangers, located in a water-filled ECT. If the temperature of RCS reach to safety shut down temperature, 215 ℃, or the operation time of PRHRS is up to 36 hrs, the event 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
Reaches RPS trip set-point by low RCP speed	$RPM = 0.9 \times RPM_{normal}$ RCP stop + 0.37 s
Reactor trip signal is generated PRHRAS is generated CMTAS is generated MSIV/FIV close start PRHRS IV open start	RPS + 1.1 s
Control rod starts to insert	RPS + 1.6 s
4 trains of CMT injection start	RPS + 2.55 s (CMTAS + 1.45 s)
MSIV/FIV close completed PRHRS IV open completed	RPS + 6.1 s (PRHRAS + 5.0 s)
End of event	PRHRAS + 36 hrs (Temp. of coolant ＜ 215 ℃)

2.4 Transient Simulation of CLOF

When the reactor trip signal was generated after RPS + 1.6 s, the decay heat was simulated as shown in Fig. 2. The decay heat induced and maintained temperature difference between in & out coolant through the core. The natural circulation in primary system could exist due to the temperature difference between in & out coolant. The amount of the heat transfer in the steam generators from the primary system to the secondary system decreased because the decay heat reduced with time, so the mass flow rate of single-phase natural circulation in the primary system also reduced. It could affect the two-phase natural circulation flow rate of secondary system.

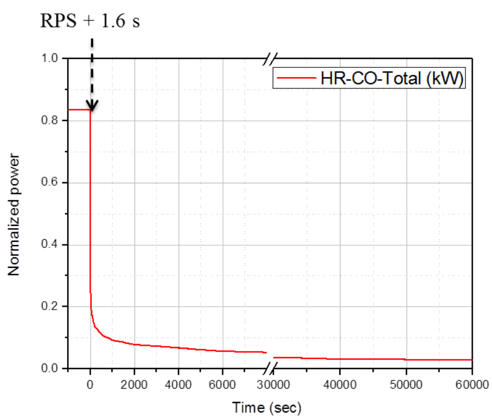

Fig. 2. Transient Simulation of CLOF
(Decay heat was applied after reactor shut down at RPS + 1.6 s.)

3. Characteristic of Natural Circulation in CLOF

After the reactor trip, the pressure of PZR decreased as presented in the first graph of Fig. 3. Because the core power of steady-state was 20% of normal operation power, the pressure rise due to the coolant temperature rise was not appeared. The pressure decrease rate tended to reduce until 4,000 s, but the gradient of pressure decrease rate turned to be steep after 4,000 s. It meant the characteristic of the heat transfer between primary and secondary system was changed near 4,000 s.

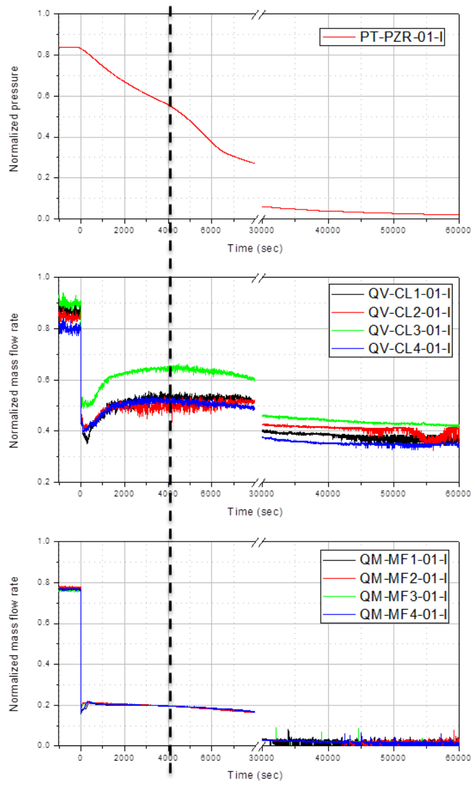

Fig. 3. Characteristic of Natural Circulation in CLOF
(Upper: pressure of PZR, middle: mass flow rate of primary system, and down: mass flow rate of secondary system)

3.1 Single-phase Natural Circulation in the Primary System

The residual heat of the primary system was continuously decreased and the temperatures of the in & out core coolant were also decreased. The mass flow rate of the primary system reduced sharply after RCP coast-down, and it was varied following the temperature difference between in & out core coolant as shown in the Fig. 4. As the temperature difference deceased, the mass flow rate of natural circulation increased during 1,000 s after reactor trip. From 1,000 s to 4,000 s, the slope of mass flow rate reduced and the mass flow rate reached the peak value. In this term, the temperature difference was almost constant. The mass flow rate decreased when the temperature difference reduced after 4,000 s. The trends of the temperature difference and the mass flow rate can be explained with Eq. (1). It is definition of Ra number with a heated length (L) for natural circulation. Even it is useful for external heat transfer on the heated wall, but the basic concept can be referred. The temperature difference between in & out coolant (ΔT) plays as a potential to induce the natural circulation. According to the experimental results, the trend of the mass flow rate of natural circulation was determined by the temperature difference between in & out core coolant (dT in the Fig. 4).

$$\mathrm{Ra_L} = \mathrm{Gr_L}\,\mathrm{Pr} = \frac{(\beta \Delta T)\, g L^3}{\nu^2}\mathrm{Pr} \qquad (1)$$

Even the temperature difference between in & out core coolant deceased during 1,000 s after reactor trip, but the absolute value was larger than after 1,000 s. It could induce a rise of the mass flow rate of natural circulation. The temperature difference between in & out core coolant was almost constant from 1,000 s to 4,000 s. It could produce a stable mass flow rate of natural circulation, but the slope of mass flow rate in the primary system decreased slightly as shown in the Fig. 4. It was because that the amount of heat transfer in the steam generator with secondary system varied with time.

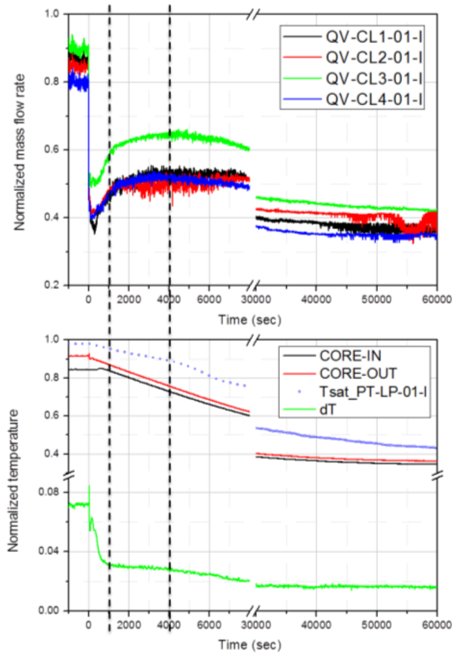

Fig. 4. Characteristic of Single-phase Natural Circulation in the Primary System

3.2 Two-phase Natural Circulation in the PRHRS

The two-phase natural circulation in the secondary system with the PRHRS was induced by heat transfer in the steam generators. The main feed water was injected into inlet of the steam generators and it changed to the steam by the decay heat from the primary system. It was delivered to the heat exchanger merged in the ECT and condensed as feed water again. The ECT of PRHRS was a final heat sink for removal of decay heat from primary system through steam generators in the secondary system. Therefore, the relationship between the primary system, the secondary system, and the ECT should be analyzed together. The aforementioned significant timings of primary natural circulation were 1,000 and 4,000 s. As shown in Fig. 4 and 5, the temperature difference between in & out core coolant sharply decreased until 1,000 s and the main feed water temperatures also decreased. The abrupt fall of feed water temperatures indicated the amount of the heat transfer in the ECT was excessive than the heat source from the steam generators during 1,000 s. And the main feed water temperatures rebounded near 1,000 s. It meant that a difference between heat source and sink reduced. The timing of the rebounding was consistent with the timing of the stable temperature difference between in & out core coolant. It indicated that balance between heat source and sink by natural circulations in the primary and secondary system turned to be stable. After rebounding, the gap of temperature between the main steam and the feed water was decreasing with time. It could be explained with thermal mixing in the ECT. During the 1,000 s, the temperature of ECT increased partially on centerline (TF-ECT1-03A) as shown in Fig. 6. The temperature of upper part of ECT (TF-ECT1-01A) increased after 1,000 s and the temperature of lower part of ECT (TF-ECT1-05A) increased near 4,000 s. It indicated that there was a delay time for heat convection of water pool in the ECT. The capability of heat sink from the ECT decreased with time due to thermal saturation of water pool, so the feed water temperature increased again after 4,000 s. It reduced the temperature difference between main steam and feed water. Therefore, the mass flow rate of PRHRS also decreased after 4,000 s due to the reduced potential of natural circulation (Fig. 5). The stable mass flow rate of PRHRS was maintained (Fig. 5) from 1,000 s to 4,000 s. In fact, the mass flow rate of PRHRS was controlled by orifices to simulate a design mass flow rate.

4. Conclusions

The CLOF test was carried out with SMART-ITL in the KAERI. The single-phase natural circulation in the primary system and the two-phase natural circulation in the secondary system were analyzed together according to the time dependent conditions with experimental data. The characteristics of the heat transfer concerned with the two different natural circulations caused by the temperature differences in the primary and secondary system were meaning to find out the physical trends of non-LOCA accident in the prototype reactor, SMART. Also, it was confirmed that the capability of the PRHRS was enough to remove the anticipated decay heat after reactor shut-down due to the CLOF accident.

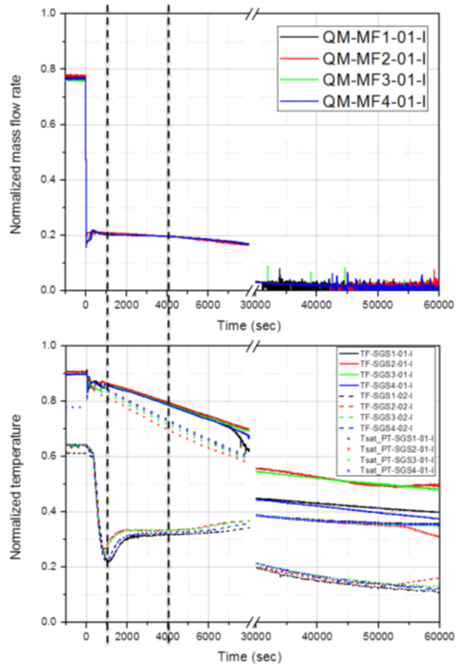

Fig. 5. Characteristic of Two-phase Natural Circulation in the Secondary System

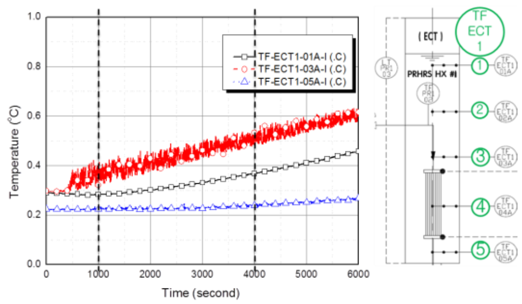

Fig. 6. Temperatures of ECT (1st train of PRHRS)

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