Characteristics of Natural Circulation in Reactor Coolant System of Integral Type Small Modular Reactor, SMART

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1. Introduction

The system-integrated modular advanced reactor, SMART, is an integral type small modular reactor which was developed by Korea Atomic Energy Research Institute (KAERI) [1]. A single pressure vessel contains all of the major components such as a pressurizer (PZR), core, steam generator (SG), and reactor coolant pump (RCP). SMART-integral test loop (SMART-ITL or FESTA) for integral thermal-hydraulic experimental investigations was constructed to validate design basis accidents (DBA) and system performance tests [2]. A previous experimental study about complete loss of reactor coolant system flow rate (CLOF) accident simulation with SMART-ITL was introduced [3]. In the previous study, it was confirmed the natural circulation in the reactor coolant system (RCS) was determined by the thermal potential due to difference of core inlet/outlet coolant temperatures. In this study, a new evidence of additional potential for increase of RCS natural circulation flow rate has been found after CLOF accident occurred.

2. Comparison of Experimental Facilities

In this section, introductions about two test facilities, VISTA-ITL (Experimental Verification of Integral Simulation of Transients and Accidents integral test loop) [4] and the SMART-ITL, are described briefly. Especially, different geometry of two facilities is a significant parameter for distinction of natural circulation characteristic.

2.1 VISTA-ITL

Fig. 2 presents schematic of VISTA-ITL constructed by KAERI. It is a small-scale integral effect test facility to investigate thermal-hydraulic characteristics of the SMART. It was designed to simulate several types of anticipated accident scenarios in the SMART with reduced height. As the VISTA-ITL is a reduced height test facility, the thermal-hydraulic behavior is 1.664 times faster than one in the prototype reactor, SMART. The detail explanations about components of VISTA-ITL, for example, a primary system, secondary system and passive residual heat removal system (PRHRS) are described in the previous study [5, 6]. In this study, the natural circulation flow rate in primary system of VISTA-ITL will be used as a reference trend of loop-type reactor.

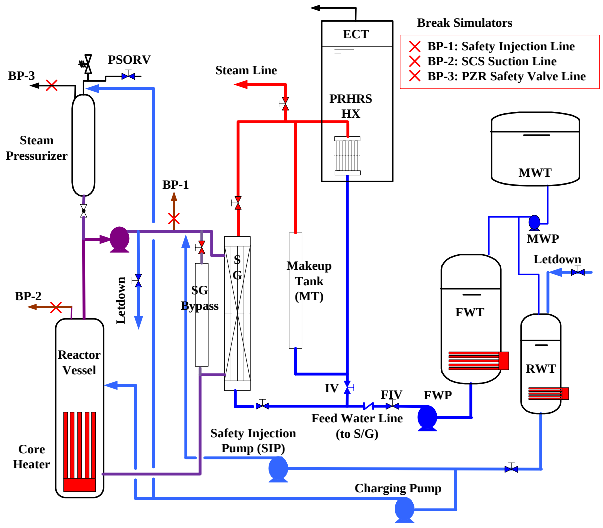

Fig. 1. VISTA-ITL with PRHRS [5]

2.2 SMART-ITL

Fig. 3 shows schematic of SMART-ITL which is a large-scale integral effect test facility with preserved height and 1/49th scaled down area and volume. It was designed following a three-level scaling method of Ishii and Kataoka [7]. The comparison of scaling ratios with VISTA-ITL and SMART-ITL is summarized in Table I [6]. The maximum core power with electric heaters is 2.0 MW, which is about 30% of the scaled full power. The design pressure and temperature of SMART-ITL are 18.0 MPa and 350℃. It is enough to simulate several types of the anticipated accident scenarios. The major components of the SMART-ITL consist of a RCS (similar to the primary system in VISTA-ITL), 4 trains of RCP, SG, secondary system, PRHRS and passive safety injection system (PSIS). The PSIS was added after Fukushima accident, it is different component with VISTA-ITL. There are also an auxiliary system, a break simulation system, and a break measuring system. Especially, because it has an integral type reactor vessel including PZR, the effect of PZR on the behavior of primary coolant after accident simulation is different from one of loop type reactor. Even though the SGs are located outside of reactor pressure vessel (RPV) due to the reduced diameter, it is an integral type reactor. The geometric difference of reactor vessel affects the initial trend of natural circulation flow rate in the RCS. It will be discussed with experimental results in the next section.

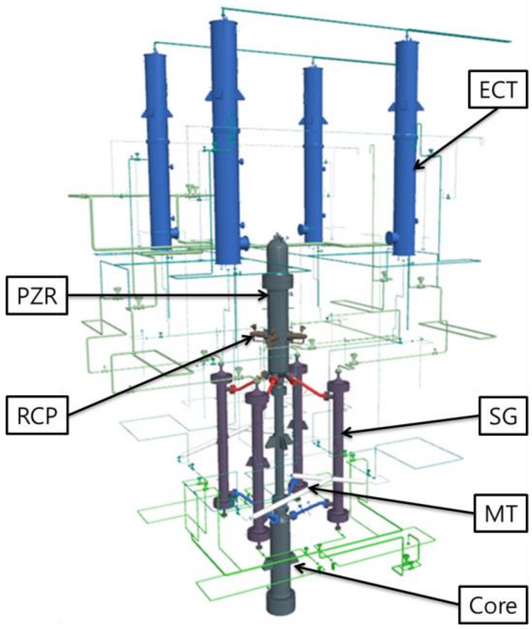

Fig. 2. SMART-ITL with PRHRS

Table I: Scaling ratios of VISTA-ITL and SMART-ITL [6]

Parameters	Scale Ratio	VISTA-ITL	SMART-ITL
Length, l_{0R}	l_{0R}	1/2.77	1/1
Diameter, d_{0R}	d_{0R}	1/21.746	1/7
Area, a_{0R}	d_{0R}^2	1/472.9	1/49
Volume, V_{0R}	$d_{0R}^2 \cdot l_{0R}$	1/1310	1/49
Time scale	$l_{0R}^{1/2}$	1/1.664	1/1
Velocity	$l_{0R}^{1/2}$	1/1.664	1/1
Power/Volume	$l_{0R}^{-1/2}$	1.664	1/1
Heat flux	$l_{0R}^{-1/2}$	1.664	1/1
Core power	$a_{0R} \cdot l_{0R}^{1/2}$	1/787	1/49
Flow rate	$a_{0R} \cdot l_{0R}^{1/2}$	1/787	1/49
Pump head	l_{0R}	1/2.77	1/1
Pressure drop	l_{0R}	1/2.77	1/1

3. Characteristics of Natural Circulation in Two Different Integral Test Facilities

3.1 Simulation of CLOF tests with two test facilities

A CLOF is one of anticipated design basis accidents (DBA), which is caused by the simultaneous failure of electrical power supply to the 4 trains of RCP. The forced convection flow in the primary system (or RCS) is completely lost and a single-phase natural circulation stars. Due to the loss of electricity, the feedwater pump and turbine in the secondary system also stop. Then, the PRHRS is operated to deliver decay heat from the core to the ultimate heat sink by a two-phase natural circulation. Both the single-phase natural circulation in the primary system (or RCS) and the two-phase natural circulation in the secondary system are activated to transfer the decay heat after CLOF accident. Even the potential of natural circulation is weaker than forced convection with RCP operation, but it is significant phenomena to remove the decay heat without electricity supply. The sequence of events (SOE) for CLOF tests with VISTA-ITL and SMART-ITL are listed in Table II [6]. The design values in the sequence of events for SMART are also presented as a reference. The full-height test facility, SMART-ITL, was able to preserve the delay time of time-dependent components. On the other hand, the reduced-height test facility, VISTA-ITL, used a scaled down delay time multiplied by 1/1.644. Exceptionally, the close of MSIV/FIV for isolation of main steam and main feedwater lines had a distortion due to mechanical limitation. The detail description about SOE is presented in the references [3] and [6].

Table II: Sequence of events for CLOF tests [6]

Event	SMART	VISTA-ITL	SMART-ITL
Transient initiation	RCP coast-down	RCP coast-down	RCP coast-down
Trip signal	HPP (or RPS)	PRZ pressure > P_{HPP} (HPP)	RCP pump signal < 90% (RPS) = RCP stop + 0.37 s
Reactor trip signal & FW stop	HPP + 1.1 s	HPP + 0.66 s	RPS + 1.1 s
PRHR actuation signal (PRHRAS) & CMTAS	HPP + 1.1 s	HPP + 0.66 s	RPS + 1.1 s
Control rod insert	HPP + 1.6 s	HPP + 0.96 s	RPS + 1.6 s
CMT Isolation Valve open	HPP + 2.2 s	N/A	RPS + 2.2 s
PRHRS IV open	PRHRAS + 5.0 s	PRHRAS + 3.0 s	PRHRAS + 5.0 s
MSIV/FIV close	PRHRAS + 5.0 s	PRHRAS + 9.0 s	PRHRAS + 5.0 s
Test end	T_{RCS} < 215°C	T_{RCS} < 215°C	T_{RCS} < 215°C

3.2 Comparison of driving force for natural circulation

Fig. 3 presents both natural circulation flow rates in the primary system of VISTA-ITL and in the RCS of SMART-ITL. As mentioned in the previous study [3], the difference of coolant temperature between inlet & outlet core is dominant potential to induce the natural circulation. The trend of the natural circulation flow rate tends to be affected by the difference of core coolant temperature. The relation of the temperature difference

(ΔT) and the natural circulation flow rate can be explained with Eq. (1).

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

It is definition of Ra number with a heated length (L) and it is similar to concept of Re number in the forced convection. Finally, the temperature difference of coolant induces a density difference of coolant between heat source (core) and heat sink (SG). The density difference of coolant is common driving force of natural circulation both in the primary system of VISTA-ITL and in the RCS of SMART-ITL (FESTA). In fact, several effects of 1) density difference of coolant, 2) relatively high energy of decay heat, and 3) inertia force due to the RCP coast-down can be reasons of the initial slope of natural circulation flow rate as shown in the Fig.3, but the effect from the density difference of coolant is relatively dominant. Even it is assumed that these reasons had similarities between the VISTA-ITAL and SMART-ITL, but it is not easy to explain the different trend from 1,700 s to 4,000 s. The natural circulation flow rate in the primary system of VISTA-ITL started to decrease after 1,700 s, but the one in the RCS of SMART-ITL continued to increase with a reduced slope until 4,000 s. It means there could be an unknown reason for increase of natural circulation flow rate in the integral type reactor.

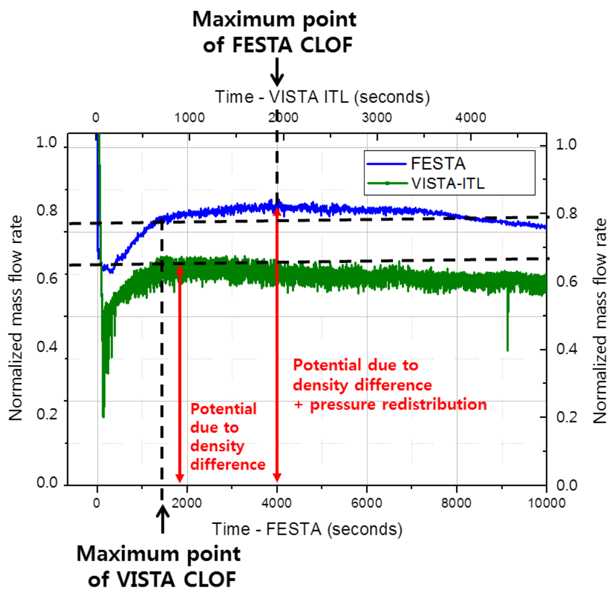

Fig. 3. Comparison results of natural circulation flow rate between in primary system of VISTA-ITL and in RCS of SMART-ITL

Fig. 4 shows a water level of core support barrel (CSB) where is an annular region for delivering coolant from the core outlet to the upper downcomer (UDC) through RCP in the SMART-ITL. The total water level of CSB was maintained as a constant value during steady-state operation before 0 s in the Fig. 4. After CLOF accident occurred, it decreased slightly but maintained above an elevation level of RCP until 4,000 s. And then, the water level of CSB decreased faster after passing the elevation level of RCP after 4,000 s. The decrease of water level in the CSB was caused by 1) pressure redistribution in the RCS and 2) shrinkage effect due to temperature decrease in the RCS. When the water level of CSB was higher than the elevation level of RCP, the additional mass flow rate was provided by pressure redistribution in the RCS. Because the shrinkage effect was common in the RCS coolant, it was not a proper reason for increasing of the natural circulation flow rate. As a result, the additional driving force by pressure redistribution increased total RCS flow rate and it was helpful to remove the decay heat of the core.

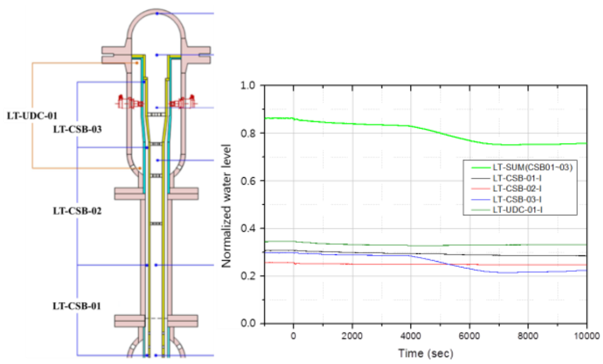

Fig. 4. Water levels (CSB and UDC) transient due to pressure redistribution in RCS of SMART-ITL

4. Conclusions

The CLOF tests were carried out with two different integral effect test facilities, VISTA-ITL and SMART-ITL in the KAERI. The characteristics of single-phase natural circulations both in the primary system of VISTA-ITL and in the RCS of SMART-ITL were investigated together. The driving force of natural circulation in the loop type test facility (VISTA-ITL) was a density difference between heat source and heat sink. On the other hand, the potentials of natural circulation flow rate in the integral type test facility (SMART-ITL) consisted of 1) density difference between heat source and heat sink, and 2) pressure redistribution in the RCS. The additional driving force by pressure redistribution increased total RCS flow rate and it was helpful to remove the decay heat of the core.

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