Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 16-18, 2018

A Discussion of Similar Tests for a CLOF Scenario using VISTA-ITL and SMART-ITL

Hyun-Sik Park [a*], Jin-Hwa Yang [a], Hwang Bae [a], Sung-Uk Ryu [a], Byong-Guk Jeon [a], Eunkoo Yun [a], Yoon Gon Bang [a], Sung-Jae Yi [a]
[a] *Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong, Daejeon, 34057, Korea*
[*] *Corresponding author: hspark@kaeri.re.kr*

1. Introduction

Saudi Arabia and Korea are collaborating to construct a couple of First-Of-A-Kind (FOAK) plants based on the results from three-year project of Pre-Project Engineering (PPE). It starts from December 2015 to prepare a Preliminary Safety Analysis Report (PSAR) and to review the feasibility of constructing SMART (System-Integrated Modular Advanced Reactor) [1] in Saudi Arabia.

The SMART design was fully assessed through various thermal-hydraulic validation tests during the licensing review process of Standard Design Approval (SDA). Among them, a small-scale integral effect test (IET) facility of VISTA-ITL (Experimental Verification by Integral Simulation of Transient and Accidents-Integral Test Loop) [2] was used to investigate various thermal-hydraulic phenomena during design basis accident scenarios such as small break loss-of-coolant accident (SBLOCA), complete loss of reactor coolant system (RCS) flow rate (CLOF), etc. The VISTA-ITL facility is a reduced height, 1/1310-volume scaled test facility with a single train of secondary system and PRHRS.

A large-scale IET facility of SMART-ITL (SMART-Integral Test Loop, or FESTA) [3] was also constructed at KAERI, and a set of integral effect tests for the design basis accident scenarios was conducted. The SMART-ITL facility is a full height, 1/49-volume scaled test facility with four trains of secondary system and PRHRS, and it can be used to investigate the integral performance of the inter-connected components and possible thermal-hydraulic phenomena occurring in the SMART design, and to validate its safety for various design basis accidents and broad transient scenarios. The role of SMART-ITL can be extended to examine and verify the normal, abnormal, and emergency operating procedures required during the construction phases of SMART.

Experiments at integral test facilities (ITFs) provide a substantial contribution to the resolution of safety issues of nuclear power plants (NPPs) and the understanding of an NPP behavior under off-normal conditions. As the typicality of the experimental data acquired in experiments at a single (scaled) test facility may be questioned in some cases due to inherent scaling distortions resulting from construction compromises and simulation constraints, there were several efforts to conduct counterpart tests or similar tests involving available ITFs at different scales and design concepts. Such experimental efforts are considered highly beneficial, not only for analyzing a light water reactor (LWR) thermal-hydraulics independent from computational analysis, but also to demonstrate the adequacy of system codes in predicting a realistic system response and to assess uncertainties of calculation models [4, 5].

Recently both VISTA-ITL and SMART-ITL were used to perform several counterpart tests for the SMART design. The test results with both VISTA-ITL and SMART-ITL have been already compared on three SBLOCA scenarios of the SIS, SCS and PSV line breaks for the SMART design [6, 7].

In this paper, the test results with both test facilities will be compared on a CLOF scenario for the SMART design. However, because some of initial and boundary conditions are not well preserved between two tests, they can be classified as similar tests.

2. Test Facilities

The VISTA-ITL [2] is a small-scale thermal-hydraulic integral effect test facility for the SMART design to investigate the thermal-hydraulic characteristics of the SMART design during the major design basis accident (DBA) conditions such as SBLOCA, CLOF, and so on, as shown in Fig.1. The major scale ratios of VISTA-ITL and SMART-ITL are summarized in Table I.

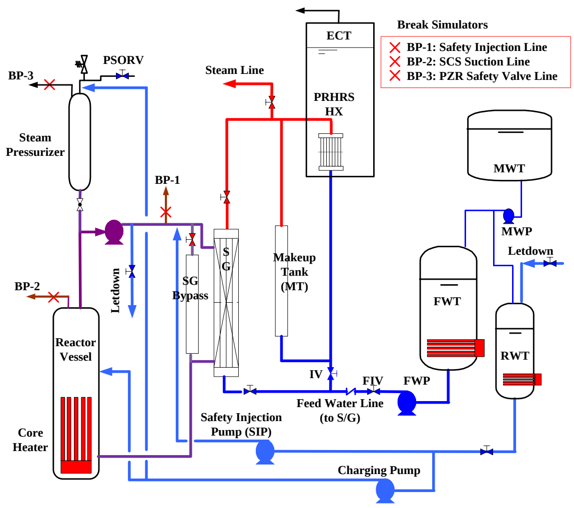

Fig. 1 Schematics of VISTA-ITL.

The scale ratios of length and area are based on the elevation difference between the core and steam generator and core flow area, respectively. The design pressure and temperature of the VISTA-ITL are 17.2 MPa and 350 ℃, respectively, and its major components consist of a primary system, secondary system, PRHRS, auxiliary system, safety injection system, break system, and break measuring system.

Table I: Comparison of major scaling parameters and their scale ratios

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

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 I. 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 ℃. 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. 2 shows a schematic of the SMART-ITL facility.

3. Similar Test Results and Discussion

As similar tests for a CLOF scenario for the SMART design, two integral effect test facilities, VISTA-ITL and SMART-ITL, were used, and their results were compared to better understand the phenomena expected to occur in the SMART design.

3.1 Typical CLOF Scenario and its Experimental Implementation

Table II shows the major sequence of events for the CLOF test. As the VISTA-ITL is a reduced-height test facility, the thermal-hydraulic behavior is 1.664-times faster in the VISTA-ITL than in the SMART design. As the SMART-ITL is equipped with passive safety injection system (PSIS) of core makeup tank (CMT) and safety injection tank (SIT), the CMT is operated together with PRHRS.

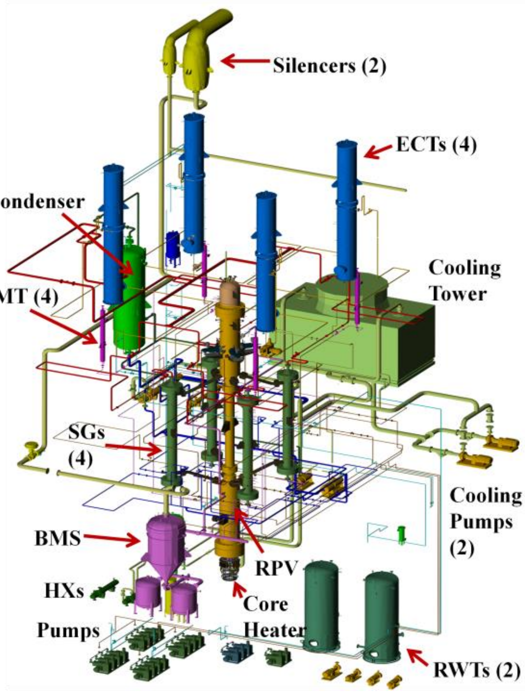

Fig. 2 Schematics of SMART-ITL.

Table II: Major sequence of CLOF scenario

Table II. Major sequence of	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)
Reactor trip signal & FW	HPP + 1.1 s	HPP + 0.66 s	RPS + 1.1 s
PRHR actuation signal	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	NA	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} < 215ºC	T_{RCS} < 215ºC	T_{RCS} < 215ºC

A CLOF accident is an anticipated operating transient, which causes a complete loss of primary flow rate by the initiation of the RCP (reactor coolant pump) coast-down owing to the failure of the electrical power supply to the

RCP. In this case, the core outlet temperature could increase rapidly owing 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 (P_{HPP}), the reactor is tripped by the reactor trip signal, which is generated with a 1.1 s (in VISTA-ITL: 0.66 s) delay. After an additional 0.5 s (in VISTA-ITL: 0.3 s) delay, the control rod is inserted. As the PRHRS actuation signal is generated by the low feed-water flow rate 1.1 s (in VISTA-ITL: 0.66 s) after the HPP, the SG is isolated from the turbine by the isolation of the main steam and feed-water isolation valves, and is connected to the PRHRS. 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 SG, and it is eventually removed by the PRHRS heat exchanger, located in a water-filled emergency cool-down tank (ECT). [8]

While the steady-state was achieved at the scaled full power conditions during the VISTA-ITL tests, it was achieved at 20% of the full power during the SMART-ITL test, and thus the HPP trip cannot be activated. In the CLOF scenario with SMART-ITL, we chose another reactor trip signal activated by the low RCP speed. This was the RCP pump signal (RPS), which was generated when the RCP speed was reduced to 90% of normal speed. It can be converted to a delay time of 0.37 s. As a result, the reactor trip occurred at 1.47 s (0.37 s + 1.1 s) after the loss of electricity. The PRHRS and Core Makeup Tank (CMT) activation signals (PRHRAS and CMTAS) were generated by the low flow rate of the feedwater at the same time. The steam generators were started to be isolated by the main steam and feedwater isolation valves (MSIV/FIV) from the turbine, and were then connected to the PRHRS. The CMT injection (4 trains) started after the RCP trip + 2.2 s (CMTAS + 1.1 s). Then, the closing of the MSIV/FIV and the opening the PRHRS isolation valve were completed after 6.1 s from the RCP trip (PRHRAS + 5.0 s), and the two-phase natural circulation occurred in the PRHRS loop. When the RCS temperature cooled down to the safety shut down temperature of 215℃, the experiment was finished. All the above sequence of events is programmed logically into the data acquisition and control system both in the VISTA-ITL and SMART-ITL facilities. The core power is properly simulated in tabular forms. The time delay after the core trip can be exactly simulated with prescribed logics.

3.2 Comparison of CLOF Test Results

Figures 3 through 8 show the comparison results of similar tests acquired using both the VISTA-ITL and SMART-ITL (or FESTA) facilities on a CLOF scenario for the SMART design. It should be noted that both VISTA-ITL and SMART-ITL have 120% and 30% power capacities, respectively. Especially for this CLOF scenario, the heat loss compensation was not provided for the SMART-ITL test but a conservative heat loss compensation was given for the VISTA-ITL test, as shown in Fig.3. It is one of main reason why these tests are classified as similar tests instead of counterpart tests. As shown in Fig. 4, their pressurizer pressures show similar trends but the decrease rate is a little slower in the VISTA-ITL than in the SMART-ITL. It is possibly affected by the relatively larger heat structure in the VISTA-ITL than in the SMART-ITL, as the small-scale IET facility has the comparatively larger heat structure than the large-scale IET facility.

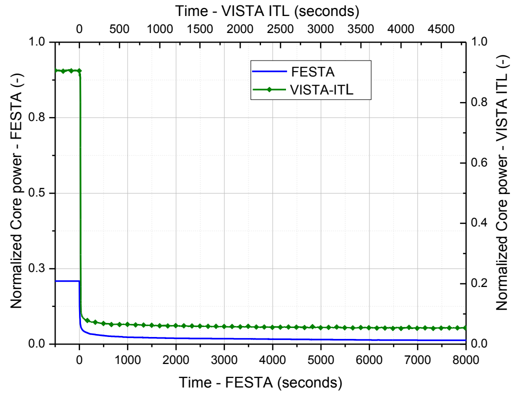

Fig. 3 Comparison of core power

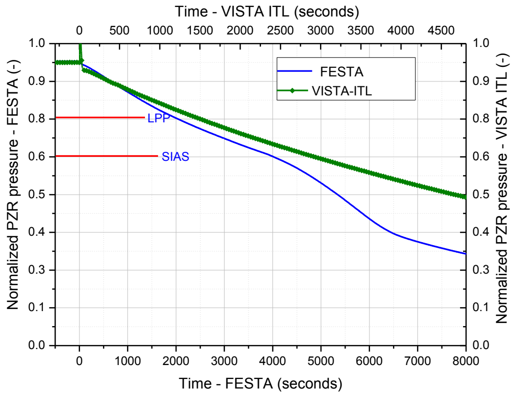

Fig. 4 Comparison of primary pressures

As shown in Fig. 5, their primary temperatures show similar trends against primary pressures. The high pressure peak in VISTA-ITL is due to the HPP trip. In SMART-ITL, because the trip is assumed to occur owing to the RPS signal, there is no significant peak.

In Fig. 6, their RCS flowrates show very similar trends with each other even though their initial values are different. The flow rate in VISTA-ITL is a little lower than that in SMART-ITL after the reactor trip. The multi-dimensional geometry in SMART-ITL can be one reason for that and more analysis is necessary as a future work. The initial RCS flow rate in the VISTA-ITL maintained 100% of the scaled value but that in SMART-ITL maintained 20% of the scaled value.

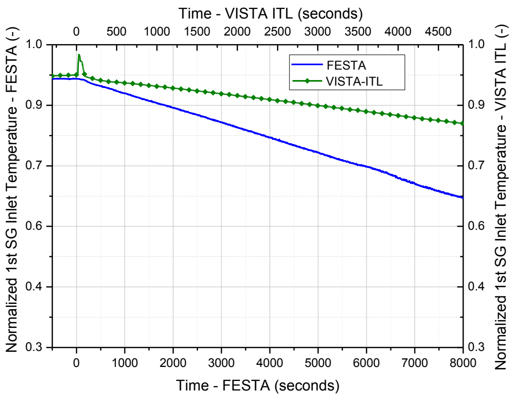

Fig. 5 Comparison of primary temperatures in the SG inlet

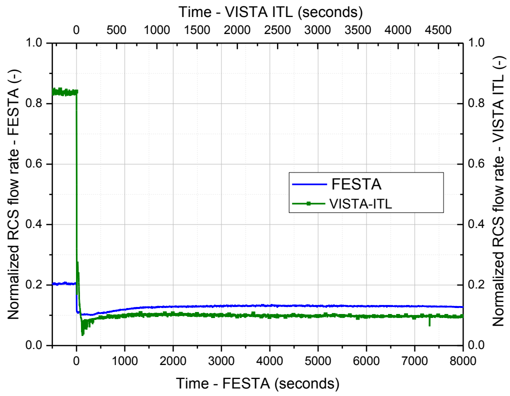

Fig. 6 Comparison of RPV flow rates in the core

As shown in Fig. 7, the collapsed core water levels of both VISTA-ITL and SMART-ITL are maintained much higher than their core top levels, and therefore the core rod temperatures does not show any abrupt increase. The geometry difference of the VISTA-ITL from the SMART-ITL is due to its modification from the original VISTA facility, and its geometry is locally distorted. However, their overall thermal-hydraulic behaviors show reasonable agreement.

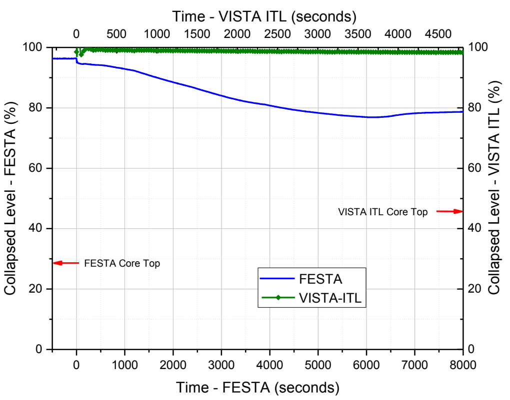

Fig. 7 Comparison of collapsed water level in the core

As shown in Fig. 8, their secondary system pressures show very similar trends with each other. In Fig. 9, their feedwater flowrates show very similar trends with each other even though their initial values are different. The initial feedwater flow rate in the VISTA-ITL maintained 100% of the scaled value but that in SMART-ITL maintained 20% of the scaled value. The flow rate in VISTA-ITL is a little higher than that in SMART-ITL after the reactor trip. It is estimated that the higher RCS temperature makes the higher flow rate in PRHRS for the VISTA-ITL compared with SMART-ITL.

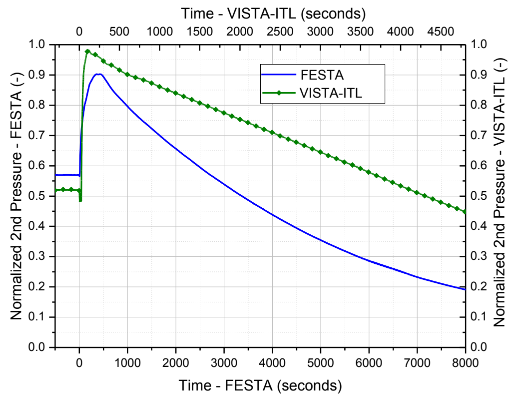

Fig. 8 Comparison of secondary pressures during the transient

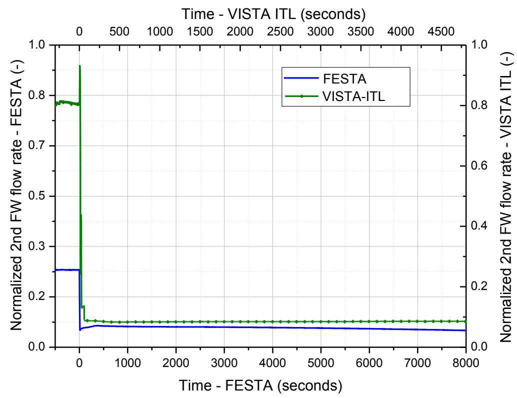

Fig. 9 Comparison of secondary system flow rates during the transient

4. Discussion and Conclusions

In this paper, results from similar tests with VISTA-ITL and SMART-ITL were discussed for the SMART design. As similar tests for a CLOF scenario for the SMART design, two integral effect test facilities, VISTA-ITL and SMART-ITL, were used, and their results were compared to better understand the phenomena expected to occur in the SMART design. The initial and boundary conditions were appropriately provided for the tests, and the overall trend of the major thermal-hydraulic parameters showed reasonable results. Although there are minor differences between the tests results from VISTA-ITL and SMART-ITL due to their different scales and intrinsic design features, it is considered that both of them provide reasonable thermal-hydraulic behaviors against the SMART design during the CLOF simulation. Therefore, these two IET facilities can be used together to simulate the thermal-hydraulic behaviors of the SMART design during various accident scenarios.

ACKNOWLEDGEMENT

This work was supported by a grant from the National Research Foundation of Korea (NRF No. 2016M2C6A 1004894) funded by the Korea government (MSIT).

REFERENCES

[1] Kim, K. K. et al., 2014. SMART: The First Licensed Advanced Integral Reactor, *Journal of Energy and Power Engineering*, 8, 94-102.
[2] Min, B. Y., Park, H. S., et al., 2014. Experimental Verification on the Integrity and Performance of the Passive Residual Heat Removal System for a SMART Design with VISTA-ITL, *Annals of Nuclear Energy*, 71, 118-124.
[3] Park, H.S., Yi, S.J., Song, C.H., 2013, SMR Accident Simulation in Experimental Test Loop, *Nuclear Engineering Int.*, November 2013, 12-15.
[4] F. D'Aurtia., G.M. Galassi, 2010, Scaling in nuclear reactor system thermal-hydraulics, Nuclear Engineering and Design, 240, 3267-3293.
[5] Bestion, D., et al., 2017, A state-of-the-art report on scaling in system thermal-hydraulics applications to nuclear reactor safety and design, Nuclear Safety, NEA/CSNI/R(2016)14, OECD/NEA.
[6] Park, H. S., et al, 2014, A Counterpart Test of the VISTA-ITL SB-SIS-07 using the FESTA for the SMART Design, *KNS Spring Meeting*, Jeju, Korea, May 29-30.
[7] Park, H. S., et al, 2014, Comparison of Counterpart Test Results with the VISTA-ITL and FESTA on SBLOCA Scenarios for an Integral Type Reactor SMART, *NUTHOS-10*, Okinawa, Japan, December 14-18.
[8] Park, H. S., et al, 2017, An integral effect test of a complete loss of reactor coolant system flow rate for the SMART design using the VISTA-ITL facility and its simulation with the MARS-KS code, *Journal of Nuclear Science and Technology*, Vol.54, No.3, pp.348-355.