Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

TASS/SMR-S Analysis on a Single-Phase Natural Circulation Phenomenon in SMART-ITL during 3-Different Operating Conditions

Hwang Bae [a*], Ji Han Chun [a], Young-Jong Chung [a], Hyun-Sik Park [a]
[a] *Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong, Daejeon, 305-353, Korea*
**Corresponding author: hbae@kaeri.re.kr*

1. Introduction

SMART (system-integrated modular advanced reactor) is a small sized integral reactor with a thermal power of 365 MWt, which is developed by the Korea Atomic Energy Research Institute (KAERI) to supply power and desalinated seawater [1]. SMART adopts a fully passive safety system, which consists of a 4-train independent passive safety injection system (PSIS) and a 4-train independent passive residual heat removal system (PRHRS) using steam generators (SGs) and secondary system lines.

Techniques used in the SMART design need to be verified through various tests including thermal-hydraulic validation tests. An integral-effect test loop for SMART (SMART-ITL) was designed to simulate the integral thermal-hydraulic behavior of SMART [2]. The objectives of the SMART-ITL are to investigate and understand the integral behavior of reactor systems and components, and the thermal-hydraulic phenomena occurring in the system during normal, abnormal, and emergency conditions. The integral-effect test data are also used to validate the related thermal-hydraulic models of the safety analysis code such as TASS/SMR-S [3], which is used for a performance and accident analysis of the SMART design.

The TASS/SMR-S code was developed to analyze thermal hydraulic phenomena under various transient and accident conditions. The 5-equation code having non-equilibrium two-phase flow thermal-hydraulic model was developed from the TASS/SMR-S V1.1 to improve a prediction capability of the thermal-hydraulic behavior of two-phase flow. The 5 governing equations consisted of mixture mass, liquid mass, mixture momentum, mixture energy, and steam energy conservation equations with various thermal hydraulic models. The integrity of the code should be checked and verified. This paper describes the validation results on the single-phase natural circulation (SPNC) test in the SMART-ITL facility. Used experimental data for a validation of the TASS/SMR-S code is from the reference [4]. The scaling and nodalization of SMART-ITL is described in Section 2.2. A modeling of SMART-ITL for the TASS/SMR-S code and a validation results for the SPNC test are produced.

2. Scaling and Nodalization of the SMART-ITL

2.1 Scaling of the SMART-ITL

Table I: Major scaling parameters of the SMART-ITL facility

Parameters	Scale Ratio	Value
Length	l_{0R}	1/1
Diameter	d_{0R}	1/7
Area	$d_{0R}^{\ 2}$	1/49
Volume	$l_{0R}\ d_{0R}^{\ 2}$	1/49
Time scale, Velocity	$l_{0R}^{\ 1/2}$	1/1
Power, Volume, Heat flux	$l_{0R}^{\ -1/2}$	1/1
Core power, Flow rate	$d_{0R}^{\ 2}\ l_{0R}^{\ 1/2}$	1/49
Pump head, Pressure drop	l_{0R}	1/1

The SMART-ITL which is a thermal-hydraulic integral effect test facility for SMART has been constructed at KAERI. The SMART-ITL has the same integral features as SMART except for the external installation of SGs and is designed according to the volume scaling method to simulate various test scenarios as realistically as possible. It is a full-height and 1/49-volume scaled test facility with respect to the SMART plant.

The fluid system of the SMART-ITL consists of a primary system, a secondary system, a passive residual heat removal system (PRHRS), a safety injection system (SIS), a shutdown cooling system (SCS), a break simulating system (BSS), a break measuring system (BMS), and auxiliary systems. The primary system has an integral arrangement except for the steam generators and is composed of reactor pressure vessel (RPV), reactor coolant pump (RCP), steam generator (SG) and primary connecting piping between RPV and SG. The secondary system of the SMART-ITL is simplified to be of a circulating loop-type and is composed of a condenser, feedwater and steam lines, and related piping and valves. All of the safety system features of the SMART plant are incorporated into the safety system of the SMART-ITL, which is composed of PRHRS and SIS. In the SMART-ITL test facility, over 1,500 instrumentations are installed to investigate the thermal-hydraulic behavior in the simulation of the various test scenarios.

The SMART-ITL facility [2, and 5] has the following characteristics: (a) 1/1-height, 1/49-volume, full-pressure simulation of SMART; (b) geometrical similarity with SMART including an integral arrangement of the primary systems; (c) a maximum 30% of the scaled nominal core power.

Scientific design of the SMART-ITL was accomplished from the viewpoints of both a global and local scaling based on Ishii's three-level scaling methodology [6].

Major scaling parameters of the SMART-ITL facility are summarized in Table I.

2.2 Nodalization of the SMART-ITL

The TASS/SMR-S code is capable of simulating the thermal-hydraulic behaviors of the SMART systems using conservation equations. Basically, the code models the plant as a set of nodes and paths to calculates the thermal-hydraulic behavior of the system such as the core power, core heat flux, coolant temperature, coolant pressure, and flow rate.

The nodalization for the SMART-ITL with the PSIS is presented in Fig. 1. The RCS, secondary system from the feedwater control valves to the turbine trip valves, SITs, CMTs and the PRHRS are modeled with nodes and paths.

The reactor coolant system consists of the heater for the core simulation, upper plenum, RCP, SG primary side, downcomer, core bottom region, and the PZR. The heater rods are modeled with 10 nodes, while the core bypass region is modeled with 3 nodes. The PZR is modeled with 10 nodes to predict a complex behavior during the early stage of a violently transient phenomenon such as LOCA.

The secondary system consists of the feedwater isolation valve, feedwater pipe, SG secondary side, steam pipe, and the steam pipe isolation valve. The four SGs are modeled with 12 nodes for each. The feedwater is set as a boundary condition using the feedwater model of the TASS/SMR-S code, while the steam lines are only modeled up to the turbine control valve.

The PRHRS is connected to downstream of the feedwater isolation valve and upstream pstream of the steam isolation valve. The PRHRS heat exchangers are modeled with 4 nodes arranged in axial direction, and the emergency cooldown tank (ECT) is modeled with 14 nodes to simulate overall circulation in the ECT.

The PSIS is connected at the RCP discharge side of the RPV. The CMT and SIT of the PSIS are modeled with 5 nodes for each component. The pressure balance line (PBL) and SIL are modeled with 8 nodes and 4 nodes, respectively.

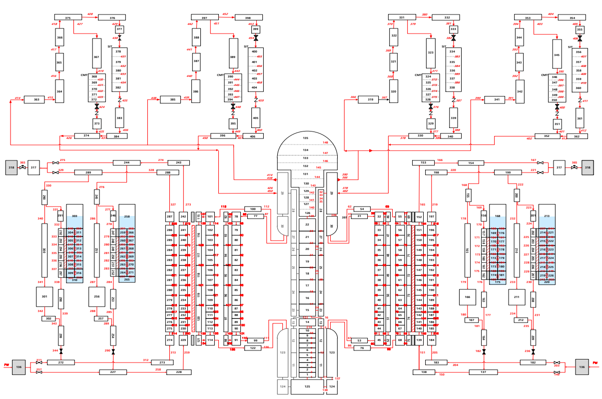

Fig. 1. SMART-ITL Nodalization for TASS/SMR-S model

3. Test and Calculation Results

3.1 Test results of the SMART-ITL

A natural circulation behavior of the RCS takes important role to reduce the thermal energy during transient situation with RCP trip and is generally driven by the buoyancy and gravity between heat source and sink. It is helpful to understand a practical natural circulation on the SMART what carries out and analyzes robust-bounding tests using SMART-ITL facility. A single phase natural circulation test using SMART-ITL was carried out through 4-step test procedure as startup operation, heatup operation, steady state operation, and single phase natural circulation (SPNC) test. After steady state operation for 15% core power (STDY-15P), natural circulation (NC) test began as soon as reactor coolant pumps (RCPs) stopped. Three NC tests were sequentially conducted during 3-step core power reduction as 15% (SPNC-15P), 10% (SPNC-10P), and 5% (SPNC-5P).

Individual tests should be to maintain a quasi-steady operation for a while. Some variables such as PZR heater power, feedwater flow rate and temperature should be precisely controlled for a constant temperature and pressure of reactor coolant system (RCS) until all of conditions are reached at steady state condition. As a result, once the RCS NC flow rate that satisfies heat balance between RCS and secondary system is reached, this state is maintained for a certain time. The initial conditions and procedures for the SPNC test is shown in Table II and III, respectively. Target values in Table II stands for the nominal operation condition to apply the scale ratio of the SMART-ITL. Most of the measured values are satisfied with the target ones within 5% difference except the core power, RCS flow rate, and feedwater pressure. The measured core power is 15.92% higher than target one because the core power in the test should include the heat loss on the structures. To satisfy the temperatures of the core and SGP under this special situation, the given RCS flow rate should be higher than the target one. It is revealed that the heat balance between the RCS and secondary system is well maintained as showing the heat transfer rate on the secondary side of the SG is similar to the target core power. The target feedwater pressure means the pressure for the rated flow rate. The actual feedwater pressure is proportional to the feedwater flow rate and could not be satisfied with the target one about 15% flow rate. Table IV shows individual core powers for SPNC test such as 15% core power with RCP (STDY-15P), 15% core power without RCP (SPNC-15P), 10% core power (SPNC-10P), and 5% core power (SPNC-5P). The SPNC test was continuously carried out by stepwise reducing the core power and feedwater flow rate as listed in Table III. STDY-15P as the test ID represents a steady state test as an initial condition for SPNC test. SPNC-15P means a quasi-state SPNC test result for 15% core power after the RCP trip. SPNC-10P and SPNC-5P mean the results of quasi-state SPNC tests for 10% and 5% core power with appropriate reduction of feedwater flow rate after stepwise decreasing the core power, respectively [4].

Table II: Initial Condition for 15% core power

Parameter	STDY-15P
	Difference (%)
Core Power	15.92
Core Inlet Temperature	0.35
Core Outlet Temperature	0.24
SGP Inlet Temperature	0.35
SGP Outlet Temperature	1.29
RCS Flow Rate	13.26
PZR Pressure	0.20
PZR Temperature	-0.12
Feedwater Temperature	0.06
Feedwater Flow Rate	-1.13
SGS Pressure	-0.13

Table III: Procedures for SPNC test

Event	Remark
Initial Condition	15% Operation
STDY-15P	Steady State
RCP trip FW Flow Rate Control	Manual Control
SPNC-15P	Quasi-Steady (> 10 min.)
Core Power FW Flow Rate Control	10% Operation Manual Control
SPNC-10P	Quasi-Steady (> 10 min.)
Core Power FW Flow Rate Control	5 % Operation Manual Control
SPNC-5P	Quasi-Steady (> 10 min.)
Test End	

Table IV: Core power distribution for SPNC

State	Core power (kW)	Remarks
STDY-15P	1,295	15% core power with RCP
SPNC-15P	1,295	15% core power after RCP trip
SPNC-10P	850.4	10% core power
SPNC-5P	550.2	5% core power

3.2 Calculation results of thetas/SMR-S

Table V shows the results of the tests and calculations. The validation analysis for the SPNC was independently calculated. Individual calculation results have continuity because the previous calculation results were used as the initial condition for a present calculation. That is, to achieve a quasi-state condition for each core power, transient calculation was performed by using transient input with the SNAP file. The SPNC-15P analysis was begun by the RCP trip with the previous result for initial condition, STDY-15P. The same methods were applied to the SPNC-10P, and -5P with additional control to appropriately reduce the feedwater flow rate. The boundary conditions such as the core power, feedwater flow rate, and feedwater temperature are well given by the input values for all of cases. The calculated values such as the pressures of the PZR and the steam line, and the temperatures of the core inlet and outlet, and steam line are well predicted within 2%. The natural circulation flow rate in the RCS is slightly under-estimated in the low power and over-estimated as increasing power within 5%.

Table V: Results comparison with test and calculation

Value	STDY-15P	SPNC-15P	SPNC-10P	SPNC-5P
	Calculation/Measurement			
Core Power	100	100	100	100
RCS Mass Flow Rate	100	103	101	95
PZR Pressure	100	100	100	99
Core Inlet Temperature	100	100	100	98
Core Outlet Temperature	100	100	100	99
PZR Temperature	100	100	100	100
Feedwater Flow Rate	100	100	100	100
Feedwater Pressure	100	100	100	100
Main Steam Pressure	100	100	100	100
Feedwater Temperature	100	100	100	100
Main Steam Temperature	100	99	102	103

The calculated heat transfer rate in the steam generators secondary side (SGS) is in a good agreement with the measured one. It is the reasonable results that the heat transfer rate in the SGS is proportional to the feedwater flow rate. The heat transfer rate of SGS is important parameter in the view point of heat removal amount. The sum of heat transfer rate and heat loss is equal to the core heater power in both of the test and calculation as listed in Table VI. It reveals that thermal equilibrium is well maintained between the RCS and secondary system for each case.

Overall results calculated by the TASS/SMR-S shows reasonable prediction for the measured values. The capability of the TASS/SMR-S is evaluated using the test results of the SMART-ITL with regard to a single phase natural circulation (SPNC).

Table VI: Heat balance between test and calculation

Value	STDY-15P	SPNC-15P	SPNC-10P	SPNC-5P
	Calculation / Measurement (%)			
Core Power	100	100	100	100
Heat Removal through SG-Secondary	100	100	101	101
Heat Balance (Core Power - MSMF)	100	101	95	96

4. Conclusion

Validation of the TASS/SMR-S models was performed using the test results of SMART-ITL on single-phase natural circulation (SPNC).

The validation results showed that the overall thermal-hydraulic behaviors from a primary system and secondary system were properly predicted. The natural circulation in the RCS was predicted reasonably by the code. However, the TASS/SMR code under-predicted the natural circulation of the RCS as the core power was decreased.

REFERENCES

[1] S. W. Choi, “General System Description of SMART NSSS,” S-001-NA000-000, Rev. 01, 2017.

[2] H. Bae, “Facility Description Report of FESTA,” KAERI/TR-7294/2018, 2018.

[3] H. R. Kim, “TASS/SMR-S Code Technical Report: Vol. 1: Code Structure, Models, and Solution Methods,” S-917-NS464-001, Rev. 01, 2017.

[4] E. G. Yun, “Quick Look Report for SMART-ITL Single Phase Natural Circulation (SPNC),” FESTA-TR-17-06, Rev. 0, 2017.

[5] H. S. Park, et al., “SMR accident simulation in experimental test loop,” Nuclear Engineering International, pp. 12-15, November 2013.

[6] M. Ishii and I. Kataoka, “Similarity Analysis and Scaling Criteria for LWRs Under Single Phase and Two-Phase Natural Circulation,” NUREG/CR-3267, ANL-83-32, Argonne National Laboratory, 1983.