Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

MARS-KS Analysis on an Integral Effect Test of CLOF (Complete Loss of RCS Flowrate) for the SMART Design

Hyun-Sik Park [a*], Jin-Hwa Yang [a], Byong-Guk Jeon [a], Hwang Bae [a]
[a] *Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong, Daejeon, 34057, Korea*
[*] *Corresponding author: hspark@kaeri.re.kr*

Keywords : MARS-KS, Integral Effect Test, CLOF, SMART-ITL, SMART

1. Introduction

A set of integral effect test were successfully performed to provide data to assess the capability of the system analysis code for the SMART design [1] using the SMART-ITL facility [2]. Among them there is a complete loss of reactor coolant system (RCS) flow rate (CLOF) scenario. The steady-state conditions were achieved to satisfy initial test conditions presented in the test requirement, its boundary conditions were accurately simulated, and the CLOF scenario for the SMART design was reproduced properly using the SMART-ITL facility [3, 4]. Previously a similar test was performed for the CLOF scenario with the VISTA-ITL facility [5] and was analyzed using the best-estimate system analysis code of MARS-KS [6] to provide a reasonable simulation results against the measured thermal-hydraulic data [7]. In this paper, the test results from the SMART-ITL were analyzed using the MARS-KS code to assess its capability to simulate a CLOF scenario for the SMART design.

2. Simulation Results on the CLOF Test

2.1 Nodalization and Input Preparation

Figure 1 shows the MARS-KS nodalization used for the SMART-ITL facility. The nodalization includes the reactor coolant system (RCS), secondary system (SS), passive safety injection system (PSIS), and passive residual heat removal system (PRHRS). The RCS loop contains the main components, such as the heater rods, reactor pressure vessel, pressurizer, RCP, RCP discharge region, SG primary side, and downcomer region. The core region is connected to two heat structures modeling 304 heater rods, which has about 30% scaled full power of SMART. The model of the fuel (9.5 mm diameter) is divided into 12 axial nodes. The pressurizer component is connected to the upper part of the reactor pressure vessel. The thermal inertia of the primary side is properly considered using the heat structure to simulate the heat capacity of the wall. The secondary loop consists of a feedwater isolation valve, feedwater pipe, steam generator secondary side, steam pipe, and steam isolation valve. The feedwater header and steam header are modeled as the boundary conditions. The PSIS consists of the core makeup tank (CMT), safety injection tank (SIT) and inter-connecting pressure balancing line (PBL) and injection line (IL). Also two stages of automatic depressurization system (ADS) is connected to the top of pressurizer. The PRHRS consists of a steam line, PRHRS heat exchanger, makeup tank, check valve, PRHRS isolation valve, and feedwater line. Time dependent volumes and a time dependent junction were included for the secondary system while PRHR HX and ECT were used for the PRHRS. The secondary system was used before the PRHRS actuation signal; thereafter, the isolation valve was opened and the PRHRS was used.

For the steady-state calculation the initial and boundary conditions are set as follows; 1) the initial and boundary values of pressure, temperature flow rate, level and heater powers are set from measurement ones; 2) the heat losses from sub-regions are simulated with the heat transfer coefficients on their surface; 3) the heat balance between RCS and secondary system are achieved adjusting their heat losses; 4) In the RCS the water level of PZR, the pressure and temperature of PZR and the temperature difference of core inlet and outlet are controlled by letdown and spray, PZR heaters, and by adjusting the speed of RCP, respectively; 5) In the secondary system the pressures, temperatures and flow rate are also simulated.

The convection boundary types for the shell and tube side of SG are 160 (Zukauskas heat transfer correlation for staggered bundle cross flow shell side) and 114 (Helical S/G tube side), respectively.

2.2 Steady-State Calculation Results

The core power of the SMART-ITL were scaled down by applying the appropriate scaling ratio of 1/49 to the SMART design. Table I shows a comparison of the major parameters of the SMART design, the ideal value, test data, and MARS-KS calculation results of SMART at a 20% rated power condition. The steady-state simulation results show that most of the thermal-hydraulic parameters agreed well. A heat loss of about 168 kW was estimated and added to the core power during the test to compensate for the heat loss from the RPV. The feed water flow rate was set to match the heat balance.

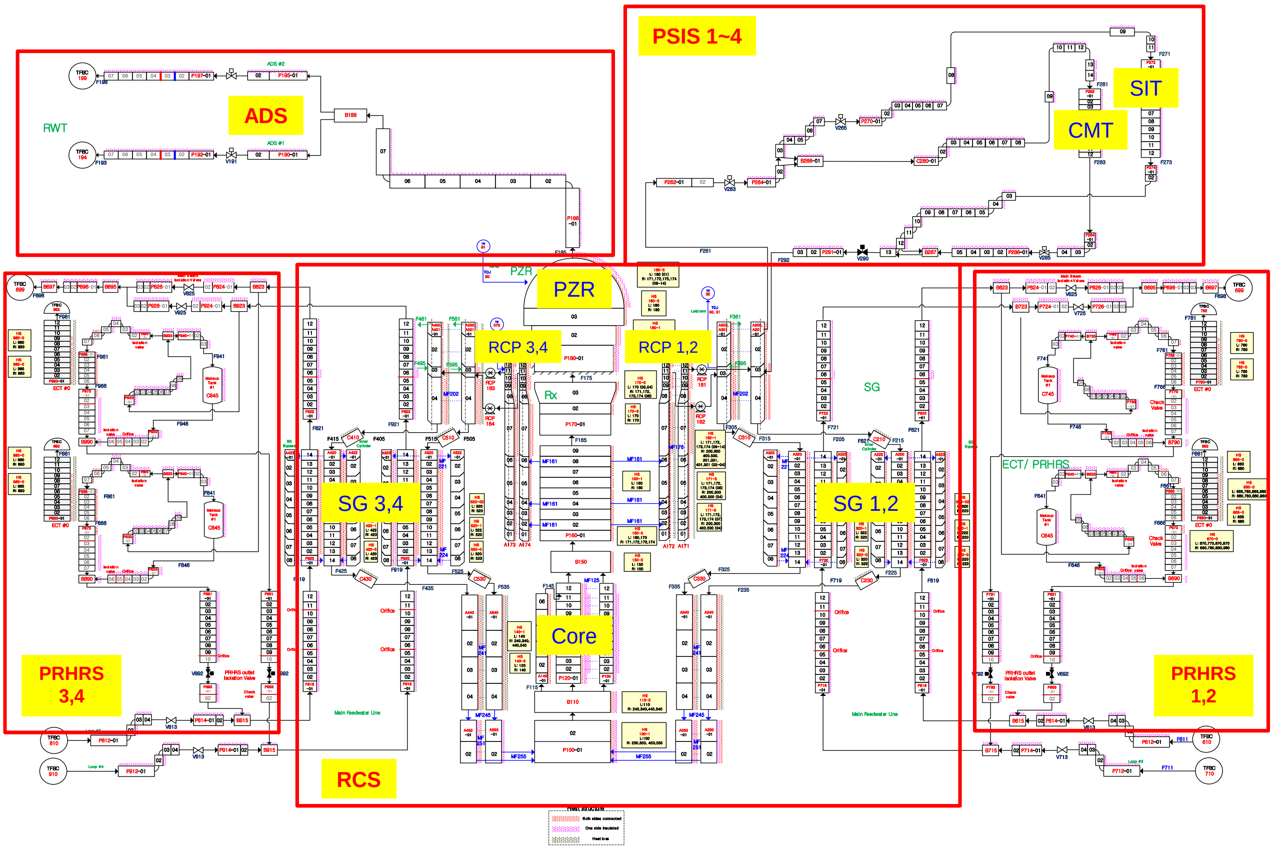


Fig. 1. MARS-KS nodalization for the SMART-ITL

Table I: Comparison of the major parameters under a steady state condition

Parameter	Target value	Test Data	MARS Cal.
Power, MW	1.49	1.67	1.67
1st Flowrate, kg/s	10.233	11.624	11.622
PZR pres., MPa	15.00	15.05	15.05
PZR fluid Temp., ℃	342.2	340.4	340.8
SG 1st inlet Temp., ℃	320.9	320.6	320.6
SG 1st outlet Temp., ℃	295.5	298.1	296.0
F.W. flow-rate, kg/s	0.778	0.769	0.768
SG 2nd inlet pres., MPa	6.71	5.71	5.67
SG 2nd inlet Temp., ℃	230.0	230.2	230.0
SG 2nd outlet pres., MPa	5.62	5.62	5.63
SG 2nd outlet temp., ℃	≧ 301.4	314.7	320.5
SG 2nd superheat, ℃	≧ 30.0	43.3	49.1

2.3 Sequence of Events for the CLOF Scenario [3]

A CLOF accident is an anticipated operating transient, which causes a complete loss of primary flow rate by the initiation of the RCP coastdown owing to the failure of the electrical power supply to the RCP, for example, station black-out. 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 coastdown, 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 setpoint, the reactor is tripped by the reactor trip signal, which is generated with a 1.1 second delay. However, since the SMART-ITL is operated in 20 % of full power of prototype, SMART, the HPP cannot be reached. In this event scenario, we select an alternative setpoint of RCP pump signal (RPS) for trip signal. The RPS is activated when the RPM of RCP decreases down to 90 % of normal operation RPM. It can be switched as a time delay of 0.37 seconds. As a result, the reactor trip signal occurs after RCP stop with 0.37 seconds + 1.1 seconds delay. At the same time, the PRHR actuation signal (PRHRAS) and CMT actuation signal (CMTAS) are generated by the low feed-water flowrate. Also the SGs are started to be isolated from the turbine by the main steam and feed-water isolation valves, and be connected to the PRHRS. After an additional 0.5 second delay, the control rod is inserted. When RPS + 2.2 seconds (CMTAS + 1.1 seconds), the 4 trains of CMT injection start. After 6.1 seconds from RPS (PRHRAS + 5.0 seconds), MSIV/FIV close and PRHRS IV open 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 emergency cool-down tank (ECT). If the temperature of RCS reach to safety shut down temperature, 215 ℃, or the operation time of PRHRS is up to 36 hours, the event can be finished.

The major sequences of events for the CLOF test, in the test and simulation, were compared in Table II. The decay-power-curve was successfully given for both the test and the MARS-KS simulation. The reactor trip occurs by the RPS or HPP. For the present case trip occurs due to the RPS and it was precisely predicted. That prediction is related to adequate representation of the primary water natural circulation and heat transfer rates through the SG.

Table II: Comparison of a major sequence of a CLOF test

Event	SMART	SMART-ITL-Test (s)	SMART-ITL-Simulation (s)
Transient initiation	RCP coast-down	0	0
Trip signal	RPS (or HPP)	0.37	0.38
Reactor trip signal & FW	RPS + 1.1 s	1.47	1.48
PRHR actuation signal (PRHRAS) & CMTAS	RPS + 1.1 s	1.47	1.48
Control rod insert	RPS + 1.6 s	1.97	1.98
CMT Isolation Valve open	RPS + 2.2 s	2.57	2.58
PRHRS IV open	PRHRAS + 5.0 s	6.47	6.48
MSIV/FIV close	PRHRAS + 5.0 s	6.47	6.48
Test end	T_{RCS} < 215°C (or less than 36 hours)	8,120	9,495

2.4 Transient Calculation Results

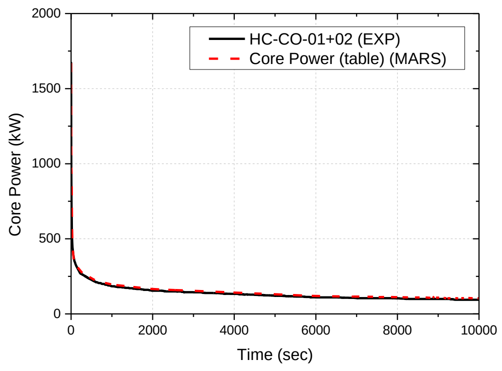
Figure 2 show the variations of the major parameters of the core power, the primary and secondary pressures, primary and secondary temperatures, flow rates in the RCS and PRHRS loop and the heat transfer rate through SG, respectively. The SMART-ITL data and its simulation results were in good agreement for the major thermal-hydraulic parameters with a slight difference. First of all, the decay heat curve provided for the test was properly given as input during the simulation, as shown in Fig. 2(a). The pressurizer pressure is well simulated in general but is under-predicted in the later phase, as shown in Fig. 2(b). It is noted that the pressure trend is changed near 4,000 s in the test data. The decrease rate of pressurizer pressure tends to reduce until 4,000 s but thereafter it turns to be steeper in the test. The pressure decrease rate slows down earlier in the MARS-KS simulation than in the test and it is steeper after 6,000 s. Figure 2(c) shows the secondary system pressure. The MARS-KS code over-estimated the peak pressure of the test data, which was caused by the low heat transfer rate through SG, as shown in Fig. 2(d) from 0 second to about 500 seconds. Because PRHRS HX was slowly uncovered, active heat removal by the PRHRS was delayed. However, after the HX was uncovered, the overall trend of the secondary system pressure was well simulated.

As shown in Fig. 2(d), the heat transfer rate through SG was well matched throughout the whole period. For the initial transient period of 500 s until about 2,000 s the flow rate is more fluctuating but the overall heat transfer is almost similar. However, after about 6,100 s, there are some fluctuation during a short period and afterwards slight over-prediction in the MARS-KS simulation.

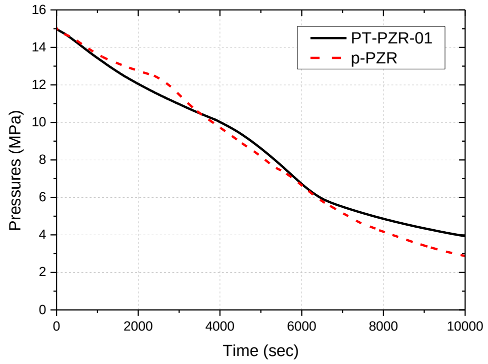
Figures 2(e) and 2(f) show the temperatures of the SG primary and secondary sides, respectively. Fluid temperatures both in the primary and secondary sides of SG show the similar trends. However, the primary side temperatures decrease a little slowly in the MARS-KS calculation. The secondary steam temperature keeps higher values in the MARS-KS calculation than in the test and the recovered feedwater temperature is higher in the MARS-KS calculation due to its high temperature in the primary side.

The MARS-KS code predicts lower mass flow rate than the test data in the primary loop of RCS, as shown in Fig. 2(g). It predicts the mass flow rate in RCS very well until 4,000 s but thereafter it under-predicts the test data with the maximum difference of about 26% and the difference at 10,000 s is about 16%. The lower RCS flow rate in the simulation is estimated that the pressure loss was high throughout the primary loop in the simulation.

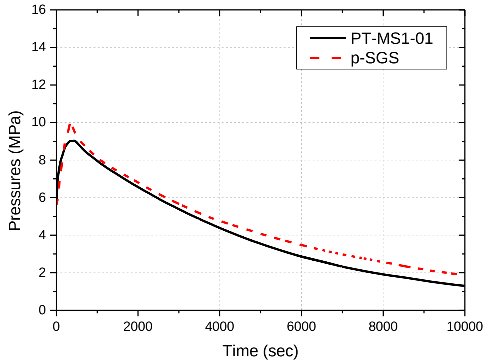
Figure 2(h) shows the secondary system flowrate. The MARS-KS code predicts slightly higher mass flow rate than the test data in the secondary loop of feedwater, SG, main steam and PRHRS. It predicts the mass flow rate in PRHRS very well until 4,000 s but thereafter it over-predicts the test data. The maximum difference is about 14% at 10,000 s.



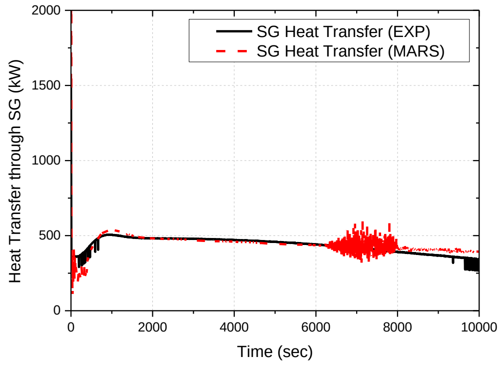
(a) Core power



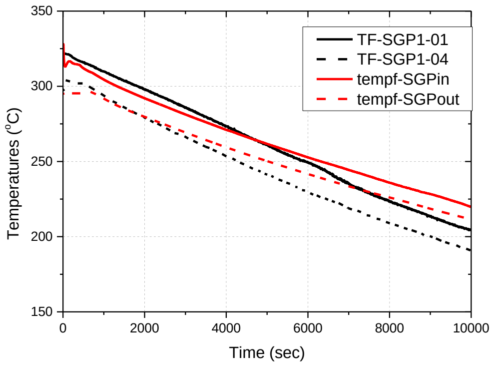
(b) Pressurizer pressure



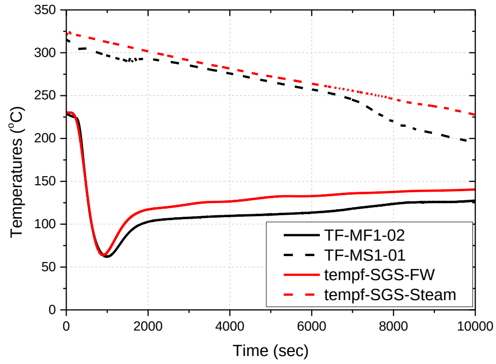
(c) Secondary system pressure



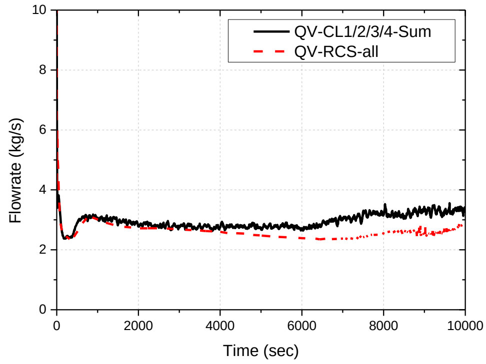
(d) Heat transfer rate through SG



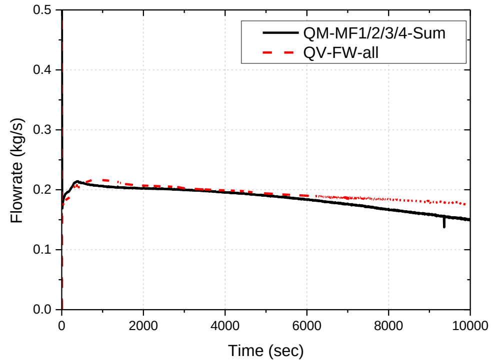
(e) SG primary side temperatures



(f) Secondary system temperatures



(g) RCS flow rate



(h) Secondary system flowrate

Fig. 2 Comparison of transient calculation results

3. Conclusions

An integral effect test for the CLOF scenario was successfully performed to provide data to assess the capability of the system analysis codes for the SMART design. The CLOF test results were simulated using the MARS-KS code to assess the simulation capability for the CLOF scenario of the SMART design.

The measured thermal-hydraulic data from the test were properly simulated using the MARS-KS code. However, there are still some discrepancy between the test and simulation results such as higher RCS temperatures. It is estimated that more accurate simulation is possible with further consideration on the heat loss through the heat structure, etc.

REFERENCES

[1] K. K. Kim, et al., SMART: The First Licensed Advanced Integral Reactor, Journal of Energy and Power Engineering, 8, 94-102, 2014.

[2] H. S. Park, S. J. Yi, C. H. Song, SMR Accident Simulation in Experimental Test Loop, Nuclear Engineering Int., November 2013, 12-15, 2013.

[3] J. H. Yang, et al., "Test Report on the Complete Loss Of RCS Flowrate (CLOF-01) of SMART-ITL with the Passive Safety Injection System," KAERI/TR-6863/2017, 2017.

[4] J. H. Yang, et al., "Experimental Study of Natural Circulation in Complete Loss of Coolant Flow Accident with SMART-ITL," Korean Nuclear Society Spring Meeting, Jeju, Korea, May 18-19, 2017.

[5] H. S. Park, et al., "A Discussion of Similar Tests for a CLOF Scenario using VISTA-ITL and SMART-ITL," Korean Nuclear Society Spring Meeting, Jeju, Korea, May 16-18, 2018.

[6] B. D. Chung, et al., Development and Assessment of Multi-Dimensional Flow Models in the Thermal-Hydraulic System Analysis Code MARS, KAERI/TR-3011/2005, 2005.

[7] H. S. Park, et al., "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, 54(3), 348-355, 2017.