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Analysis of SMART-ITL PRHRS Performance Test with MARS-KS

Jin-Hwa Yang [a*], Hwang Bae [a], Sung-Uk Ryu [a], Byong Guk Jeon [a], Eunkoo Yun [a], Sung-Jae Yi [a],
Yeonsik Cho [b], Hyunjin Lee [b] and Hyun-Sik Park [a]
[a]*Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong-gu, Daejeon, 305-353, Korea*
[b]*SENTech, 105, Sinildong-ro, Daedeok-gu, Daejeon, Korea*
[*]Corresponding author: f1yjh@kaeri.re.kr

1. Introduction

One of small modular reactors (SMRs), SMART (system-integrated modular advanced reactor), is an integral type reactor which was developed by Korea Atomic Energy Research Institute (KAERI) [1]. All of the major components such as a pressurizer (PZR), core, steam generator (SG), and reactor coolant pump (RCP) are located in a single pressure vessel. For thermal-hydraulic integral effect tests, SMART-integral test loop (SMART-ITL or FESTA) was constructed to simulate design basis accidents (DBA) scenarios and system performance tests [2]. Passive Residual Heat Removal System (PRHRS) is one of passive safety systems in the SMART, and system performance test of PRHRS is essential to complete a design of safety system. In this paper, PRHRS performance test results and MARS code calculation results will be presented.

2. Experimental Facility

2.1 SMART-ITL

Fig. 1 shows components of SMART-ITL which were designed to maintain a natural circulation effect with preserved height and 1/49 scaled down area and volume. It followed a three-level scaling method of Ishii and Kataoka [3]. The scaling ratios of SMART-ITL are summarized in Table I [4]. The maximum core power with electric heaters is 2.0 MW and it is about 30% of the scaled full power. The design pressure and temperature of SMART-ITL are 18.0 MPa and 350℃. The major components of the SMART-ITL consist of a reactor coolant system (RCS), 4 trains of RCP, SG, secondary system, PRHRS and passive safety injection system (PSIS). There are also an auxiliary system, a break simulation system, and a break measuring system.

2.2 PRHRS of SMART-ITL

PRHRS of SMART-ITL prevents over-heating and over-pressurizing of the RCS. When an accident occurs, decay heat from core is transferred to the secondary system through SG. The PRHRS uses the main steam (MS) lines and main feedwater (MF) lines for two-phase natural circulation loop. There are four trains in the test facility and each train is composed of an emergency cooldown tank (ECT), PRHRS heat exchanger (PHX), PRHRS makeup tank (PMT), valves, and pipes as shown in Fig. 2 [4]. When the PRHRS actuation signal is activated, the two-phase natural circulation loop is immediately triggered to start opening the bypass valves, which connect to the secondary system. Then, the steam from the MS lines is injected into the PHX submerged in the ECT, and the condensed water is returned to the MF lines to cool down the primary system through steam generators. The PRHRS was designed to reduce the coolant temperature under the shutdown cooling initiation temperature within 36 h after an accident and to maintain it for at least another 36 h.

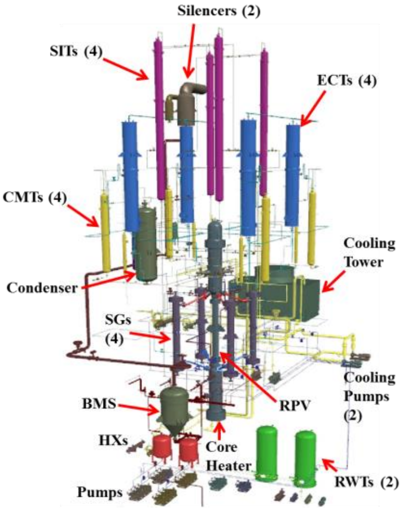

Fig. 1. Components of SMART-ITL

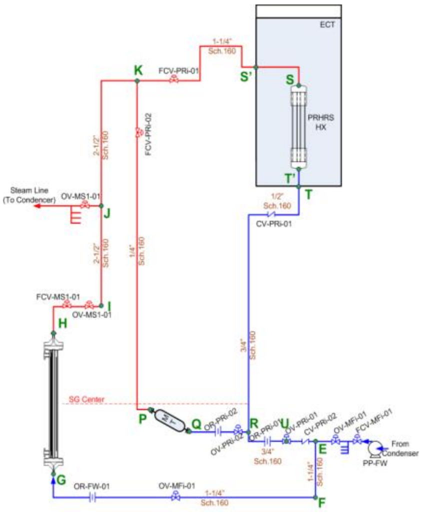

Fig. 2. Schematic of PRHRS in SMART-ITL [4]

Table I: Scaling ratios of SMART-ITL [4]

Parameters	Scale Ratio	SMART-ITL
Length	l_{0R}	1/1
Diameter	d_{0R}	1/7
Area	d_{0R}^2	1/49
Volume	$d_{0R}^2 \cdot l_{0R}$	1/49
Time scale	$l_{0R}^{1/2}$	1/1
Velocity	$l_{0R}^{1/2}$	1/1
Flow rate	$a_{0R} \cdot l_{0R}^{1/2}$	1/49

3. Experimental Results & MARS Code Calculation

3.1 Test procedure

SP-PRHRS-01 test for evaluating the performance of the PRHRS was carried out maintaining the RCS and ECT temperatures at 300℃ and 100 ℃, respectively, as presented in Table II. Since the initial temperature of ECT was 100 ℃, the heat transfer by evaporation was a main heat sink in the tests. Four steady-state experiments were performed during more than 10 minutes while reducing the train number of PRHRS in the order of 4 → 3 → 2 and 1. The main objective of SP-PRHRS-01 test was to quantify the transferred heat according to the number of PRHRS. Another objective was to quantify the heat loss of RCS without PRHRS. In this study, the heat loss of RCS was considered in the code calculations.

Table II: Test conditions

Test ID	Temp. (℃)		Number of Trains	Description
	RCS	ECT		
SP-PRHRS-01	300	100	4→3→2→1	Steady-state

3.2 MARS-KS code simulation

MARS-KS [5] which is one of system analysis codes was used for validation. Fig. 3 presents nodalization of SMART-ITL which contains RCS, PZR, RCP, SG, secondary system and passive safety systems, i.e., PRHRS and PSIS. Four different input file packages were prepared for code simulation following the number of PRHRS train and each input file package was divided into 'steady-state with active secondary system' and 'steady-state with the PRHRS'. Initial and boundary conditions for 'steady-state with active secondary system' calculation were defined by experimental data and it was simulated using the MF pump operation. The two-phase natural circulation of PRHRS was simulated in the 'steady-state with the PRHRS' calculations without the MF pump operation. In this study, 'steady-state with the PRHRS' calculations without the MF pump operation was used for comparison.

3.3 Comparison results between experimental data and code calculation results

Table III shows the comparison results between experimental data and code calculation results. The results were normalized based on the experimental data according to the number of PRHRS trains. The core power and PZR pressure were stably maintained in the code calculation. The RCS flow rate tended to increase following the reduction of train numbers. It was linked with temperature difference between core inlet and outlet. The combined effect of heat source from core and heat sinks from the PRHRS and heat loss of RCS loop determined the RCS flow rate and temperature difference between core inlet and outlet. Thus, when the RCS flow rate tended to increase, temperature difference between core inlet and outlet tended to decrease.

The experimental data of secondary side of SMART-ITL were asymmetric when the 4, 3, and 2 trains of PRHRS were operated. The normalized values could not reflect this trend, but asymmetric condition made differences between two benchmarks. The calculation results in the first and second trains show better agreement with experimental data in cases with 4 trains and 3 trains of PRHRS operation tests. On the contrast, the third and fourth trains had the differences over 5%. When 4 trains of PRHRS were operated, the maximum difference was 8% of the feedwater and main steam pressures in the fourth train. The feedwater temperature of the third train was 7% less than the experimental data. When the 3 trains of PRHRS were operated, the feedwater temperature of the third train had a largest gap as 13%. And the feedwater and main steam pressures in the fourth train were 9% and 8%, respectively. When 2 trains of PRHRS were operated, the feedwater and main steam pressures in the fourth train were overestimated and the feedwater temperature of the third train was underestimated with gaps over 9%. The code inputs were modeled as symmetric geometric conditions, for example, pipe length, location of valve and flowmeter, and so on. However, the configuration of SMART-ITL is not totally symmetric due to a limitation of room for instruments location. It could induce asymmetric heat loss according to the train of secondary system or PRHRS.

The difference of heat distribution modeling in the ECT could affect the asymmetric result. The ECT of SMART-ITL has upper and lower headers to support heat exchangers. These parts have quite large volumes, and steam and condensed water also pass through it. In the code calculation, the upper and lower parts of ECT were simulated as insulated. If it could be simulated with quantified heat distribution fraction, the analysis results of heat transfer through ECT by code calculation could be advanced.

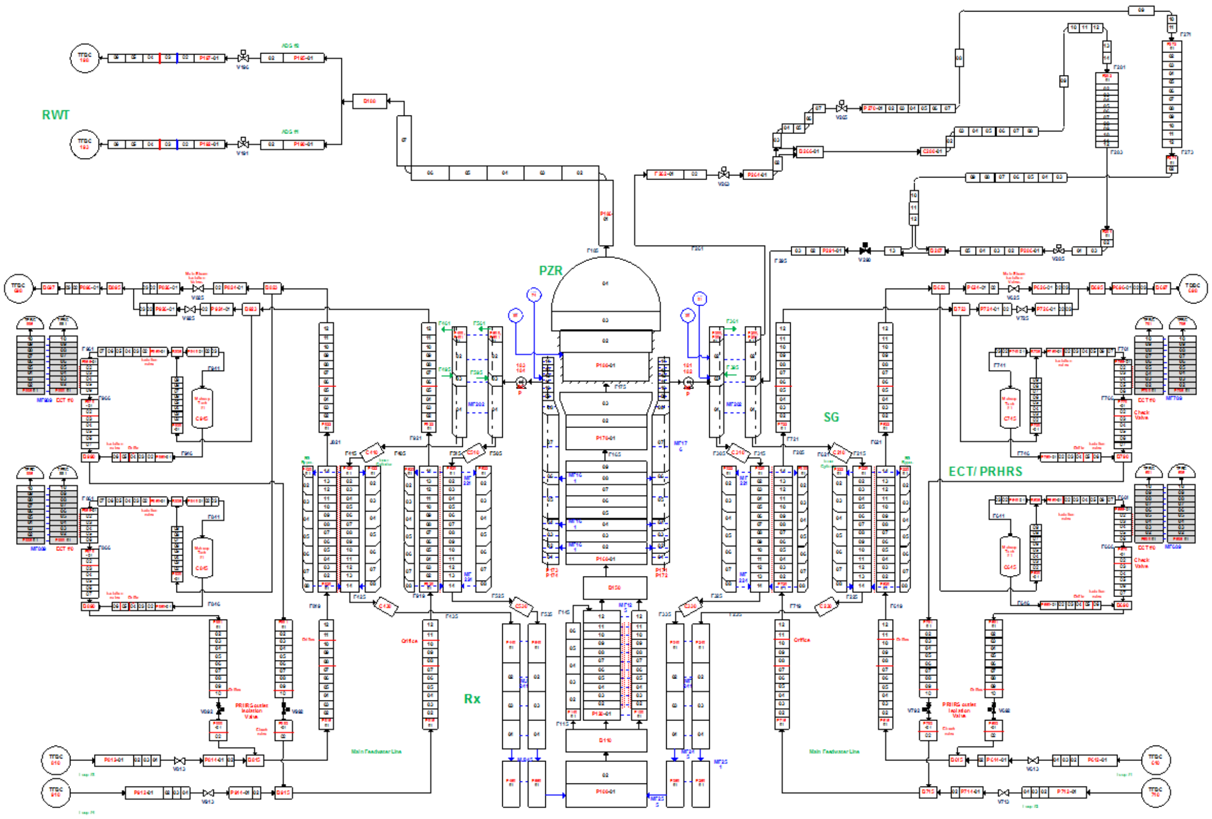

Fig. 3. Nodalization of SMART-ITL [6]

Table II: Comparison of experiments and calculation results (normalized)

	Physical variables		Number of PRHRS			
			4	3	2	1
RCS	Core power		1.00	1.00	1.00	1.00
	PZR pressure		0.99	0.99	0.99	0.99
	RCS flow rate		0.99	1.02	1.03	1.07
	Core out temperature		1.00	0.99	1.00	0.96
	Core in temperature		1.00	0.99	1.00	0.95
	Temperature difference (core in/out)		1.12	1.11	1.05	1.05
Secondary side	Feedwater flow rate		1.03	1.01	1.01	1.00
	Feedwater pressure	1	1.01	-	-	-
		2	1.03	1.02	-	-
		3	1.01	1.00	1.02	-
		4	1.08	1.09	1.09	1.02
	Feedwater temperature	1	0.99	-	-	-
		2	1.02	1.03	-	-
		3	0.93	0.87	0.91	-
		4	1.01	1.02	1.03	1.00
	Main steam pressure	1	1.02	-	-	-
		2	1.05	1.01	-	-
		3	1.03	1.00	1.02	-
		4	1.08	1.08	1.11	1.02
	Main steam temperature	1	0.99	-	-	-
		2	1.01	0.99	-	-
		3	0.97	0.97	0.98	-
		4	1.02	1.00	1.01	0.92

4. Conclusions

The steady-state experiments to evaluate system performance of PRHRS in the SMART-ITL were conducted. The code calculations using MARS-KS were also carried out. The comparison results between experiments and calculations were similar to each other. The minor difference can be advanced if the heat loss and distribution of heat transfer in the component, i.e. ECT, could be quantified by experimental data. The modeling of heat loss or component will be modified following the quantified results.

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