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Experimental Assessment on Main Flow Path and Heat Loss of SMART-ITL Facility during Specific Steady-State Conditions

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1. Introduction

A number of safety related tests and system performance tests were conducted using SMART-ITL [1] facility, integral effect test facility of SMART. All tests begin by maintaining a steady state for a period of time that simulates the normal operation of the proto-plant. Steady-state conditions using SMART-ITL can maintain the thermal hydraulic characteristics such as pressure and temperature of the whole system the same as those of the proto-type nuclear reactor, although they have restrictions imposed by the scale ratio of the test facility and the scaled full power of the core heater. This is possible because SMART-ITL has the same vertical length as SMART [2] and the facility volume is scaled down to scale ratio. This paper deals with the characterization of the SMART-ITL system, focusing on the thermal hydraulic parameters of the reactor coolant system during steady-state operation to perform various simulations conducted over the past several years. From the temperature distribution, we tried to understand the main flow path of the reactor coolant flowing along the reactor pressure vessel. The thermal energy of the reactor coolant system due to the core heater power, the heat transfer characteristics between the reactor coolant system and secondary system, and the heat loss of the reactor coolant system in terms of heat balance are evaluated.

2. Methods and Results

2.1 Scaling of the SMART-ITL

SMART-ITL [3] was designed following a three-level scaling methodology [4] consisting of integral scaling, boundary flow scaling, and local phenomena scaling. 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 full-scaled power. The design pressure and temperature of SMART-ITL can simulate the maximum operating conditions, that is, 18.0 MPa and 350 ℃. The scaling ratios adopted in SMART-ITL with respect to SMART are summarized in Table I.

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

2.2 Specific design of the steam generators

The SMART SG design is composed of eight SGs. On the other hand, four steam generators are installed in the SMART-ITL facility [5]. A single SG of SMART-ITL is scaled down to simulate two SGs of SMART. Each steam generator is composed of 15 helically coiled tubes, a bypass region and an inner cylinder region, and an outer vessel. Helical tubes consist of 4, 5, and 6 tubes in inner, middle and outer regions, respectively, as shown in Fig. 1.

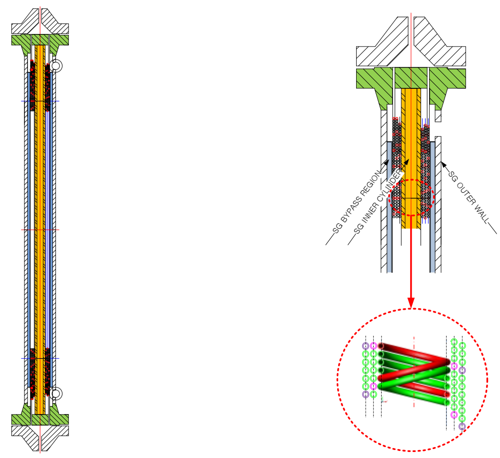

Fig. 1. Configuration of SMART-ITL SG.

The reactor coolant enters the inlet of the SG from the top and flows down through the shell side, forming a countercurrent flow with respect to the secondary feedwater flow inside the tube. The secondary feedwater enters to the inlet of the SG tubes from the bottom, flows upward through the helical tubes, and becomes a superheated steam at the outlet of the SG tubes.

All reactor coolant system (RCS) components except for steam generators are equipped in a reactor pressure vessel (RPV) similarly to the SMART design. As the scaled-down annular downcomer of SMART-ITL is not enough to contain the SGs, four SGs are installed outside of the RPV using two connecting pipes above and below each SG like hot and cold legs, respectively, which facilitates relevant measurements and maintenance.

2.3 Method and Procedure for the SG Performance Evaluation Tests

SG performance tests were carried out as reducing the number of SGs under certain core heater power conditions. It should be shown that the condition satisfying the normal operating condition determined for each test was maintained for a certain period of time. The flow rate ratio of the reactor coolant system and the secondary system must maintain the same as the core power ratio. The pressure and temperature of each system should be the same as the rated operating conditions.

For example, when simulating 25% operation using four steam generators, the core heater power and flow rate through the core inlet and outlet in the reactor coolant system should satisfy 25% of the rated operating condition. That is, the flow rate per reactor coolant pump and steam generator primary side should be maintained at 6.25% of the rated condition. Pressurizer pressure, and inlet and outlet temperatures of the core and steam generator primary side should satisfy the design values at 100% rated operating conditions. In the secondary system, the flow rate by the feedwater pump should maintain 25% of the rated operation, and the feedwater temperature and steam pressure should satisfy the design values at 100% operating conditions.

In this state, when two steam generators are used, the same flow rate as the 50% operating condition passes through the steam generator, and when one is used, the same flow rate as the 100% operating condition passes through the steam generator. The test is to reduce the number of steam generators. At 25% operating condition, a number of steam generators is reduced from four SGs (SGP-25P-T4), two SGs (SGP-25P-T2) to one SG (SGP-25P-T1), respectively. The steam generator performance test matrix is summarized in the Table II.

Table II: Test matrix for the steam generator performance

Test ID SGP-	Core heater power (%)	RCS flow rate (%)	Feed water flow rate (%)	No. of SGs	SG flow rate per a train (%)
25P-T4	25	25	25	4	25
25P-T2	25	25	25	2	50
25P-T1	25	25	25	1	100

2.4 Steady State Condition

During the SG performance evaluation tests, it was found that the steady-state conditions were maintained for a certain period of time. In all of the steady-state tests, major parameters, including the reactor coolant system and secondary system, were confirmed to have reached a steady state, followed by measurements for about 1,200 seconds. The operating conditions for individual tests are shown in Table III [6], which compares the target values and test results for each test as a percentage. The tests that reduced the number of steam generators were conducted at a 25% operating condition. The mean values of the measured variables during the steady state were well-maintained. All of the measured variables, except the core power, feedwater pressure, and steam temperature, were in good agreement within the range of 5%. The core power should be set higher than the target value in view of the heat loss in the reactor pressure vessel, including the reactor coolant system. It is also more important that the feedwater pressure varies with the feedwater flow rate, but reaches the steam pressure rather than the feedwater pressure. This is known to have no significant effect on the steady-state result since the satisfaction of the superheat more than 30 ° C above the saturation temperature for the steam pressure is given priority.

Table III: steady state condition comparison with target values and measured values (%)

Parameter	Target Value	25P		
		T4	T2	T1
Core Power	25	27.8	27.5	26.9
Core Inlet Temperature	100	100.2	100.3	100.5
Core Outlet Temperature	100	100.2	100.4	100.7
SGP Inlet Temperature	100	100.1	100.5	100.9
SGP Outlet Temperature	100	101.1	100.7	101.6
RCS Flow Rate	100	98.4	91.2	96.2
Pressurizer Pressure	100	100	99.9	100.2
Pressurizer Flued Temperature	100	99.9	99.9	95.9
Pressurizer Water Level	100	98.6	102.4	99.5
SGS Feedwater Temperature	100	100.4	100.0	99.9
SGS Steam Temperature	100	104.1	105.4	105.8
SGS Feedwater Line Flow Rate	100	99.7	99.2	95.0
SGS Feedwater Line Pressure	100	87.2	91.3	105.8
SGS Steam Line Pressure	100	100.0	100.0	99.7

2.5 Main Flow Path Assessment using the Temperature of the Inner Rising Regions

Overall flow path of the RCS in the SMART-ITL passes through core, RCP, SG, and then returns to core again. The rising flow of the core outlet returns to the core inlet as the downward flow. A specific flow path is a little complicate because an internal structure of the reactor pressure vessel (RPV) in the SMART-ITL consists of triple layers, which physically divide individual flow paths as shown in Fig. 2 [7]. The two inner layers are divided into a central region and an intermediate region. The central region including a bundle of core heaters corresponds to the inside of a cylinder geometry with the several flow path holes that upward flow easily moves into the next region. The rising annular flow in the intermediate region moves into outer region, which includes the RCP discharge region, SG cassettes, and lower plenum. Upward flow direction in two inner layers is changed to downward flow direction in the outer layer through the RCP. The downward flow changes to upward flow in the inlet of the core heater bundle.

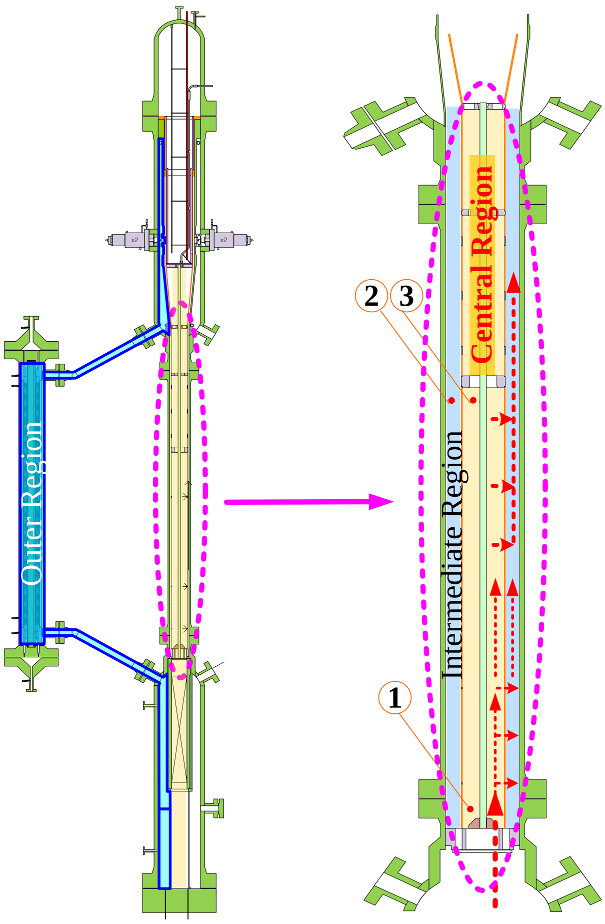

Fig. 2. Triple-flow region of SMART-ITL.

To investigate the main flow path between two inner layers, the temperature distribution in the points 1 to 3 of the Fig. 2 is shown in Fig. 3 and 4. The points 1 and 2 are located in the core outlet region and middle section of the central region, respectively. The point 2 is located in the middle section of the intermediate region. The temperature sequentially decrease along the points 1, 2, and 3 due to the friction resistance and thermal dissipation (Fig. 3). The temperature of the point 2 that is located in the intermediate region is higher than that of the point 3 that is located in the central region. It reveals that the hottest fluid moves from the bottom of the central region (point 1) to the middle of the intermediate region (point 2). That is, the temperature of point 3 is higher than that of the point 2 because most of the fluid in the point 1 of the central region moves to the next region before arriving the point 2. This can be assessed by the comparison of regional wall temperature with point 1 and 2 as shown in Fig. 4. Inside wall temperature of the point 1 is higher than outside wall temperature of the same point. It means that most of the fluid flows upward. Inside wall temperature of the point 2 is higher than outside wall temperature of the same point. It means that the fluid flows partially upward direction in the central region and mostly horizontal direction to the intermediate region. In addition, fluid temperature of the point 2 is higher than that of the point 3. It also reveals that the main flow path moves from the central region to the intermediate region before arriving the point 2 and 3.

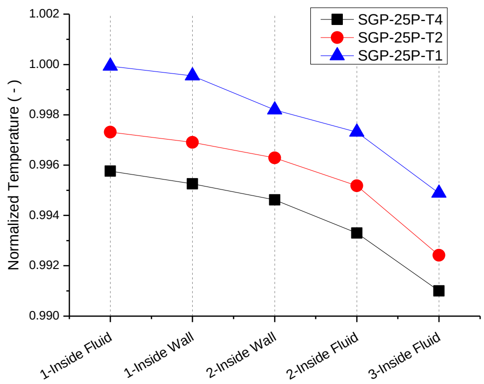

Fig. 3. Temperature distribution along the main upward flow path of SMART-ITL.

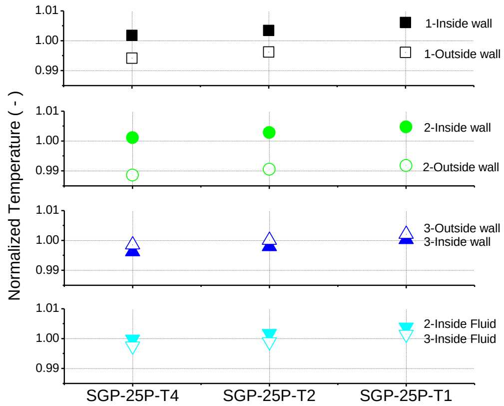

Fig. 4. Comparison with the wall and fluid temperature in two-inner region of SMART-ITL.

2.6 Heat Loss Assessment using Thermal Equilibrium

Core heater power of the SMART-ITL is higher than the target value in all tests. The core power in the tests (SGP-25P-T4, -T2, and -T1) for reducing the number of steam generators at 25% power condition shows a distribution of about 10% higher than the target value

[6]. On the other hand, the heat removal rate on the steam generator secondary side is distributed within 2.0% of the target core power in all tests listed in Table IV. It shows that heat loss occurs at the outer wall of the reactor pressure vessel while the heat removal amount of the steam generator satisfies the target value. The difference between the actual core power on the reactor coolant system and the heat removal amount on the steam generator secondary side is 8.9%, 7.7%, and 9.5% for SGP-25P-T4, T2, and T1, which reduce the number of steam generators under 25%, respectively. It is shown that the actual core power is about 10% higher than the target value, and the heat loss is within the same range as well.

Considering that most of the heat losses from SMART-ITL occur in the cold legs and lower down-comer (LDC) connecting steam generators and reactor pressure vessel, it seems obvious that the heat loss is reduced as the number of steam generators decreases. However, the heat loss at SGP-25P-T4, T2, and T1, which are tests to reduce the number of steam generators at the same core power, shows an approximate distribution of both the absolute value and its ratio to core power. The heat loss ratio to the core power shows a similar distribution to the target core power ratio to the actual core power. In conclusion, the heat loss evaluated from the viewpoint of thermal equilibrium shows that if the heat removal amount on the secondary side of the steam generator satisfies the target value of the core power, all of the heat to exceed the target core power are the same as the heat loss.

Table IV: Heat loss estimated by the difference from Core heater power to SGS heat removal

Parameter	25P (%)		
	T4	T2	T1
Core Heater Power	111.0	110.0	107.7
Heat Removal from SGS	101.5	101.8	97.9
Heat Loss	8.9	7.7	9.5

3. Conclusions

Three tests for evaluating the steam generator performance were conducted. First of all, the number of steam generators was reduced in the order of 4-train steam generators ⇒ 2-train steam generators ⇒ 1-train steam generator at a 25% core power condition. The test method simulating the steady-state condition and the test results were analyzed. The main data were appropriately measured within the allowable tolerances given in the test requirements.

The thermal-hydraulic parameters such as pressure, temperature, and flow rate of each system shown in the test requirements were maintained for more than 10 minutes in the steady-state condition.

The main flow path was assessed by the temperature distribution of the inner rising region that includes the central and intermediate region. It reveals that the main flow that starts the core outlet in the bottom of the central region moves to the intermediate region before the middle section of the reactor pressure vessel.

The heat loss in terms of thermal equilibrium was the same as the difference between the actual value and target value of core power when the amount of heat removal on the secondary side of the steam generator satisfied the target value of the core power.

As a result, the steam generator performance tests were well conducted based on the procedure. The measured parameters clearly revealed the thermal-hydraulic characteristics at a steady state.

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