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Experimental Study for Conceptual Validation of SMART PCCS

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1. Introduction

There are several types of passive safety system equipped in the SMART, passive residual heat removal systems (PRHRS), passive safety injection system (PSIS) with automatic depressurization system (ADS), and passive containment cooling system (PCCS). The PCCS is essential to reduce not only the temperature and pressure of containment building, but also radioactive substance after accident. The previous design concept of PCCS in the version of SMART standard design approval (SDA) [1] was using an external heat exchanger with atmosphere air and a spray on the top of containment to reduce the temperature and pressure, and radioactive substance. However, it was modified through feasibility study, because the installation cost of the external heat exchanger was too much and the spray was not enough to remove the radioactive substance against a strengthened regulation standard after Fukushima accident. Therefore, a concept of direct condensation using in-containment refueling water storage tank (IRWST) with double layer containment was selected. The newly suggested design concept suppresses the inner layer containment (dry well) with steam after accident, and reduces the amount of the radioactive substance into the outer layer containment (containment atmosphere) by condensing the steam and dissolving the radioactive substance in the IRWST as shown in the Fig. 1. The condensed steam increases temperature and level of water in the IRWST. When the cooling capacity of IRWST reduced, emergency cool-down tank (ECT) of PRHRS is used as alternative heat sink in the system. It is important to define the cooling capacity of IRWST because it determines an operating time of PCCS. Although the effect of radioactive substance dissolving in the IRWST cannot be evaluated due to the problems concerned with regulation and safety, but the cooling capacity of IRWST should be validated.

The objective of this study is a thermal-hydraulic validation of the newly suggested PCCS design concept with a scaled down test facility. The SISTA, SMART IRWST separated test apparatus, is a separated effect test facility to validate the new PCCS design concept during anticipated accidents. The design values of PCCS in the SMART were produced with MARS calculation by FNC [2]. The SISTA was constructed according to the scaled down design values. The dry well and IRWST of SISTA were designed with scaled down volumes following the Ishii's scaling method [3]. The SISTA produced experimental data for evaluating thermal-hydraulic behaviors in the major components such as dry well and IRWTS, and it is expected to be valuable for the SMART PCCS design.

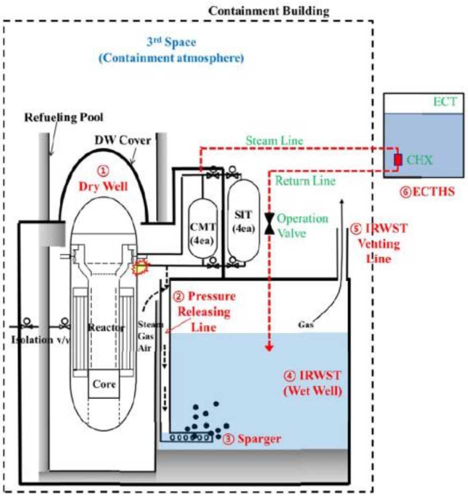


Fig. 1. Schematic of PCCS in SMART

2. Features of SISTA

Main components of SISTA are steam injection system, dry well, IRWST and containment as presented in Fig. 2. The detail descriptions are as follows.

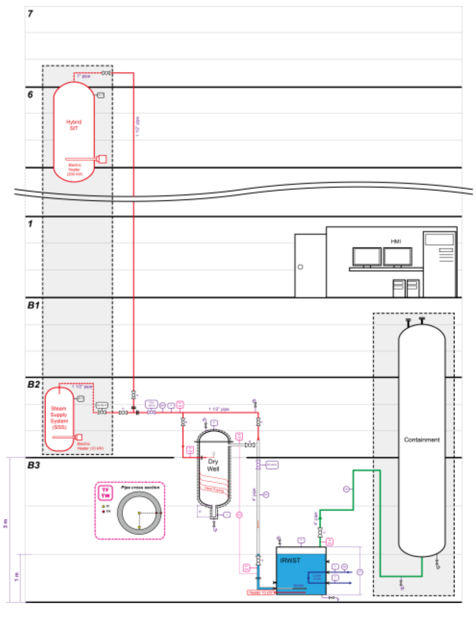


Fig. 2. Schematic of SISTA

2.1 Steam Injection System

The steam injection system is able to produce saturation steam from 0.1 MPa to 15 MPa. It is composed of a low pressure steam injection line using steam supply system (SSS) with 10 kW heater and a high pressure steam injection line using pressurizer of hybrid safety injection tank (SIT), HPZR, with 200 kW heater as shown in the Fig. 2. The SSS was designed to simulate low-flow steam condition at long term of the accident and heat up the pipe lines. It is necessary to avoid water hammer effect when high temperature steam passes through the unheated pipes. The HPZR was used to simulate high-flow steam injection condition at the beginning of the accident. In this paper, the high pressure steam injection line with the HPZR was only used, because the experiment time continued until 3,000 s.

2.2 Dry Well

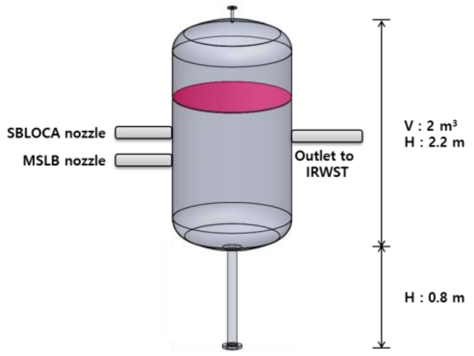
The dry well is a space in the inner layer of double layer containment in the SMART PCCS. It was simplified as a 2 m^3 cylindrical tank without inner structures as shown in the Fig. 3(a). The inner structures, for example, reactor pressure vessel, control rod assembly, core makeup tanks (CMT), and so on, were ignored in the dry well of SISTA. Two types of anticipated accidents, SBLOCA and MSLB can be simulated with different elevated inlet pipes which have a scaled down break hole. The outlet pipe to the IRWST was connected on the middle of dry well. The elevation points of inlet and outlet nozzles were determined considering elevation ratios in the prototype. The injected steam in the dry well was condensed on the inner wall. The condensed water was accumulated in a 0.8 m pipe which was connected on the bottom of dry well. The inner wall of dry well can be preheated with a tracing heater of 10 kW if it is necessary.

2.3 IRWST

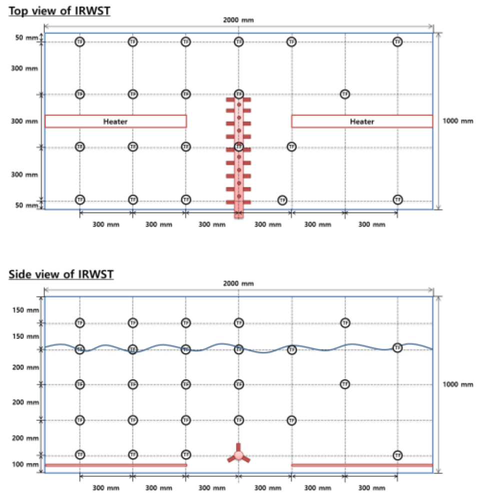
The IRWST is a heat sink in the PCCS of SMART and it was simulated as a 2 m^3 rectangular water tank in the SISTA as presented in the Fig. 3(b). The initial temperature and level of water were 50 ℃ and 0.7 m. There were 90 thermocouples in the IRWST of SISTA. The initial temperature could be adjusted with a heater of 10 kW. The mixture of non-condensable gas and steam from dry well passed through the storage water in the IRWST and the direct condensation occurred. There was a sparger which induced thermal mixing in the IRWST. It was designed to avoid a material damage from chugging effect as shown in the Fig. 3(c).

2.4 Containment

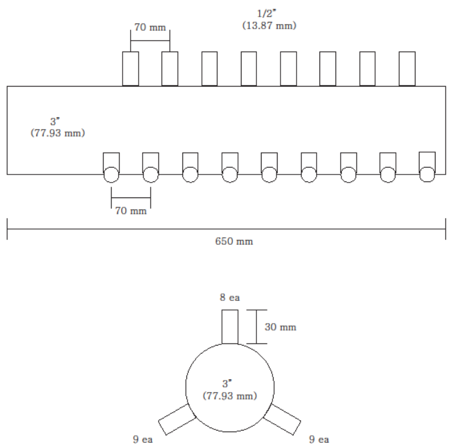
The outer containment in the SMART PCCS is a last barrier to prevent releasing gaseous radioactive material to the environment. The containment in the SISTA is a tank which is connected to the top of the IRWST. It is always opened to the atmosphere because there is not gaseous radioactive material in the experiment.



(a) Dry well



(b) IRWST



(C) Sparger in IRWST

Fig. 3. Main components of SISTA

3. Experimental Study

The main experiment with SISTA is SBLOCA simulation. Before the simulation, preliminary tests to confirm a characteristic of SISTA facility were conducted. Heat loss test of IRWST was carried out to define a heat transfer rate from IRWST to atmosphere. Steady-state mass flow rate test was conducted to produce a loss coefficient in the pipe from HPZR to dry well. The results from preliminary tests were used as references in the SBLOCA simulation.

3.1 Heat Loss Test of IRWST

The operating time of PCCS is maintained for a long time. Because the main function of the IRWST is heat sink in the PCCS, the heat loss can be an error of the component. Therefore, it is essential to define the heat transfer rate by heat loss from IRWST. Although the IRWST of SISTA is insulated with 7.5 mm insulator, there is a heat loss. Fig. 4 presents the result of heat loss test of IRWST. There are five thermocouple layers in the IRWST along vertical direction as presented in Fig. 3(b). T_avg_01 is an average temperature of top layer of the IRWST, T_avg_02, 03, 04 are average temperatures of second, third, and fourth layers of the IRWST. T_avg_05 is an average temperature of bottom layer of the IRWST. The initial temperature was 50 ℃ and it decreased about 5 ℃ during 20 hours. The heat transfer rate by the heat loss from IRWST is about 0.4 kW. The temperature of bottom layer decreased faster than other layers, because there was a thermal stratification under the heater during heat up process.

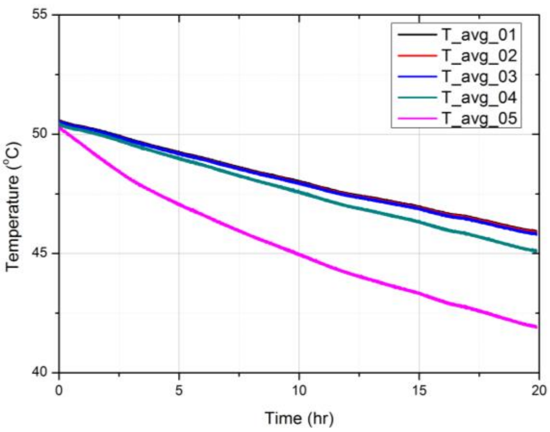


Fig. 4. Heat loss test of IRWST

3.2 Steady-state Mass Flow Rate Test

To determine a loss coefficient of pipe line from HPZR to dry well of the SISTA, steady-state mass flow rate tests were conducted. Fig. 5 shows the results of test and it is listed on the Table I. The pressure difference between HPZR and dry well was maintained by valve opening and heater power. The loss coefficient is similar when the mass flow rate is large enough to make a flow as turbulent. However, it turns to be large values due to the low mass flow rate. It indicated the flow switched as a laminar flow between case 4 and case 5. The expected range of mass flow rate is from 22 kg/min to 1 kg/min in the 'beginning of accident with abrupt mass flow rate change' step of SBLOCA simulation. Therefore, it is assumed as turbulent flow in the pipe from HPZR to dry well of the SISTA during experiment, and the loss coefficient is about 0.023.

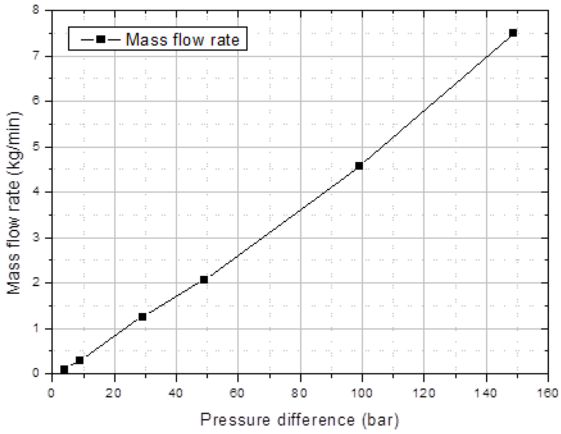


Fig. 5. Results of steady-state mass flow rate test

Table I: Results of Steady-state Mass Flow Rate Test

	ΔP (bar)	ρ (kg/m3)	$\dot{m}$ (kg/s)	k
Case1	149	96.727	0.125	0.022
Case2	99	55.463	0.076	0.022
Case3	49	25.351	0.034	0.025
Case4	29	15.001	0.021	0.023
Case5	9	5.145	0.005	0.044
Case6	4	2.668	0.002	0.113

3.3 Transient Simulation: SBLOCA

The SBLOCA was simulated with a scaled down break nozzle in the dry well. The location of intact nozzle was selected considering the ratio of break point in the SMART. The injected mass flow rate is defined in the design report produced by FNC and a reduced mass flow rate following scaling ratio was applied in the SBLOCA simulation in the SISTA.

Fig. 6 presents the mass flow rate injected into the dry well as a boundary condition. The mass flow rate in the experiment was controlled by valve opening and heater power of HPZR. The mass flow rate follows the design value well. It means the boundary condition was simulated as expected.

Fig. 7 shows the pressure in the dry well. The design value is sharply increases after break simulation, and it is maintained until 3,000 s. However, the pressure in the experiment increases with delay time and it reduces again. The pressure increase continues to 600 s and decreases after that, and the mass flow rate injected into the dry well drops at the same time.

Fig. 8 indicates the average temperature of IRWST. The initial increase rate depends on the amount of mass flow rate from dry well and it is defined by the pressure in the dry well. The design value increases faster than the one of experiment, because the transferred mass from the dry well is higher than experiment due to large pressure difference.

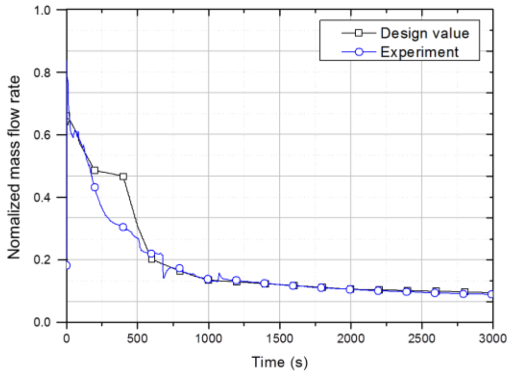


Fig. 6. Nomalized mass flow rate in SBLOCA simulation

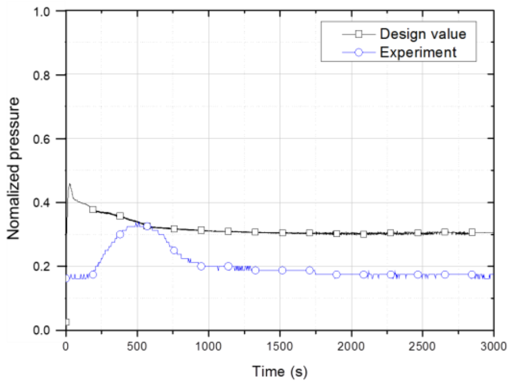


Fig. 7. Nomalized pressure in dry well

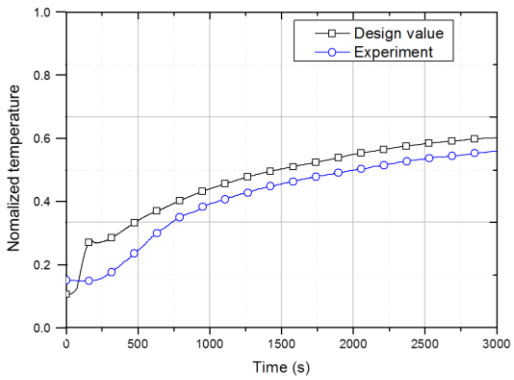


Fig. 8. Nomalized temperature in IRWST

4. Conclusions

The SISTA which is a separate effect test facility for a conceptual validation of PCCS was constructed. The main components of PCCS were reduced and simplified, but it was able to simulate a direct condensation phenomenon similar to the design values of prototype. Since the specific design values of SMART PCCS are to be determined later, the SISTA can be distorted. Even it will be different from final design values, the experimental results in this paper can be used as a valuable reference.

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