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Experimental Study of Hydrogen Behaviors Affected by Pressure Control Systems in a Reactor Containment

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1. Introduction

A spray system in a containment of a nuclear power plant (NPP) is an important means to reduce pressure inside the containment building during design-based and beyond-design accidents [1]. The containment spray controls the pressure by cooling the temperature of the atmosphere in the containment building and inducing condensation of water vapor distributed in the atmosphere [2]. Recently, nuclear power plants that have reflected a passive containment cooling system (PCCS), a heat removal device for passively decompressing the atmosphere inside a containment building, have emerged. Representative nuclear power plants that reflect PCCS include APR + [3], which improves the safety of APR1400, CAP1400 [4] in China, and AP1000 [5]. PCCS is connected to a large water tank outside the containment building to serve as a heat sink of the containment building for a long time. Since the spray system injects cooling water directly into the containment building, there are phenomena such as reduction in free volume of containment and evaporation of cooling water in the long term, while heat sinks such as a PCCS, a method of indirectly removing heat, the same problem can be ruled out.

Whether a pressure control system of a NPP containment is a heat removal method by direct contact of spray water or a heat removal method by indirect contact of a heat sink, it condenses water vapor released inside the containment building during an accident. Thus, the concentration of hydrogen can be relatively increased by lowering the concentration of water vapor by its condensation.

Conversely, the behavior of the spray droplets exchanges momentum with the surrounding atmosphere due to the frictional force at the droplet interface, thus increasing the mixing of stratified hydrogen. In the case of the heat sink including the chamber, the air cooled by the heat sink moves through the chamber to the bottom of the containment building, and suction flow occurs at the entrance of the heat sink, thereby forming a natural circulation flow throughout the containment building. Reduction of water vapor concentration in the containment building atmosphere by heat sinking and natural circulation flow affects the distribution and behavior of hydrogen as well as spray water. In this way, the operation of the spray and heat sink in the containment building greatly affects the behavior of hydrogen, so the operation of the spray and heat sink needs to be dealt with importantly from a hydrogen control point of view during a severe accident.

This study is an experimental work to evaluate the hydrogen behaviors at conditions of spray and heat-sink operations using the SPARC test facility that simulates the containment [6].

2. Test Facilities

The spray and heat-sink experiments performed in this research focus on the effect on the behavior of hydrogen by the activation of spray and heat-sink, not simply simulating the thermal hydraulic phenomenon. Therefore, in the spray and heat sinking experiment using the SPARC test apparatus, we intend to conduct an experimental study on the hydrogen behavior during the spray and heat-sink operation.

The SPARC spray/heat-sink experiment was designed to focus on two phenomena. The SPARC-SPRAY (SS) experiment is an experiment that evaluates the effect on the distribution of hydrogen when water spray is operated while hydrogen is being released, and the SPARC-SPRAY-PAR (SSP) experiment evaluates the effect of water spray on the operation of PAR. Likewise, the SPARC-HEATSINK (SH) experiment is an experiment to evaluate the effect on the behavior of hydrogen when the heat sink is operated while hydrogen is being released, and SPARC-HEATSINK-PAR (SHP) experiment evaluates the effect of heat-sink on the operation of PAR.

The SPARC pressure vessel provides a very large experimental space with a volume of 80 m^3, but considering the spray angle of the spray nozzle and the diameter of the water vapor discharge nozzle, the volume is insufficient to simulate the thermal hydraulic phenomenon in the spray condition in the containment building of the actual nuclear power plant. Therefore, it is an experimental simulation that experimentally simulates issues related to hydrogen safety. For the SPARC spray and heat-sink experiments, the main purpose of the experiment is to understand the hydrogen issues related to the operation of these containment pressure control devices and to produce experimental data to verify the analytical model.

For supplying cooling water to a spray nozzle and a heat-sink for the SPARC experiments, a cooling water supply system was constructed as shown in Fig. 1.

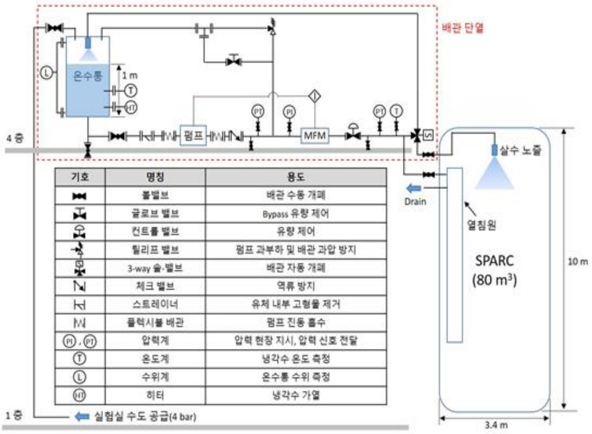


Fig. 1. Schematic of water supply system for a spray and a heat-sink

2.1 Spray system

For the SPARC spray experiment, the specifications of the spray system installed in APR1400 were referred. The spray nozzle installed in the APR1400 containment is a hallow cone type, the average flow rate per nozzle is 1 kg/s, and the volume average droplet diameter is about 300 μm. In actual APR1400 containment, about 300 spray nozzles are installed per train, and the height from the dome to the working deck is more than 40 m, so the receiving surface of the hallow cone is expected to be almost full circle. For the experiment, a full cone type spray nozzle was manufactured. In the SPARC spray experiment, the size of the droplet was selected as the equivalent factor among the specifications of the spray system installed in APR1400, and the spray angle was designed to be about 30^{o} so that the spray droplet do not enter the outlet of the PAR installed on the SPARC vessel wall in the case of a spray-PAR interaction test.

Fig. 2. Test of spray droplet size distribution

To evaluate the performance of the manufactured spray nozzle, droplet size distribution, droplet ejection angle, and droplet receiving area, a performance experiment of the spray nozzle was performed. Fig. 2 shows an experiment to measure the spray angle, the size distribution of water droplets, and so on. Fig. 3 shows the droplet size distribution of the spray nozzle.

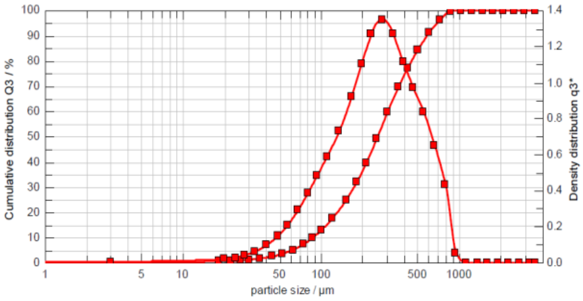


Fig. 3. Size distribution of spray droplets

The current SPARC test facility has 14 hydrogen concentration sensors and 8 relative humidity sensors installed. The detail specifications of the sensors are described in the reference [6]. The locations of the sensors are determined depending on test conditions. The arrangement of the concentration measurement sensors for the SPARC-SPARY test are depicted in Fig. 4.

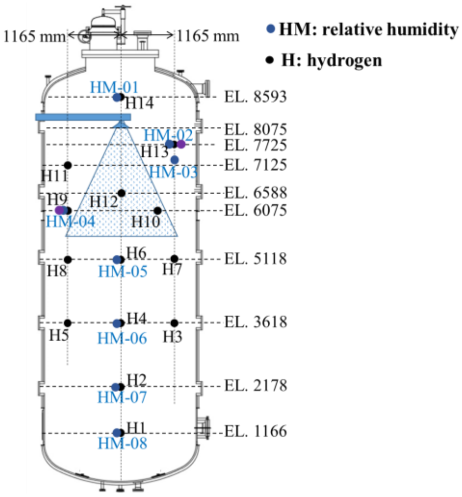


Fig. 4. Arrangement of the hydrogen and steam concentration sensors for SPARC-SPRAY test.

2.2 Heat Sink System

In order to simulate the heat-sink in a containment building such as a PCCS, a separate heat-sink for experiment was produced. In the SPARC experiment, heat-sink reduces the temperature of the atmosphere below the saturated water temperature to condense the water vapor, thereby changing the atmospheric thermal hydraulic conditions or changing the water vapor condition. The most important considerations in heat-sink design are cooling performance, minimizing flow disturbance, and natural convection induction performance (chimney effect).

In the heat-sink experiment, the cooling water was supplied to the heat-sink using the pump skid installed for supply of water to a spray nozzle, so the cooling water injected through the pump skid passes through a heat sink made of copper tube, exchanges heat with the surrounding atmosphere, and is discharged to the outside of the SPARC. Fig. 5 shows the heat-sink installed near the vessel wall of SPARC.

Fig. 5. Installation of a heat-sink in the SPARC vessel

The arrangement of the concentration measurement sensors for the SPARC-HEATSINK test are depicted in Fig. 6.

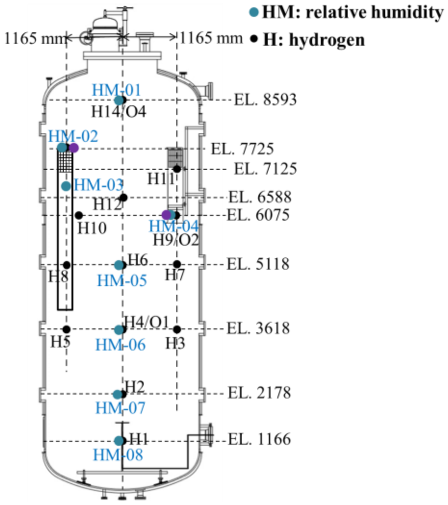


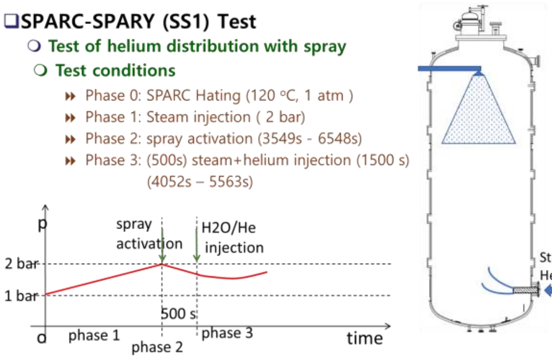
Fig. 6. Arrangement of the hydrogen and steam concentration sensors for SPARC-HEATSINK test.

3. Spray Experiment

The SS (SPARC-SPRAY) experiment is an experiment that evaluates the effect on the distribution of hydrogen when spray is operated while hydrogen is being released, and evaluates the concentration change and mixing characteristics of hydrogen due to steam condensation during spray. In the SPARC experiment, helium was used instead of hydrogen with safety considerations, so it is an experiment with an injection of steam and helium. In the SS experiment, two tests of SS1 and SS2 according to the SPARC atmospheric conditions before spray operation were conducted.

3.1 SS1 Test Conditions

Fig. 7 shows the conditions of the SS1 test. SPARC was preconditioned to a temperature of 120°C and a pressure of 1 atm. during phase 0. In phase 1 steam was injected to increase the SPARC vessel pressure up to 2 bar. In the SS1 test, spray was activated 500s before the steam and helium injection, and it was continuously operated until end of the experiment.



❑**SPARC-SPARY (SS1) Test**

- ❍ **Test of helium distribution with spray**
  - ❍ **Test conditions**
    - Phase 0: SPARC Hating (120 °C, 1 atm)
    - Phase 1: Steam injection (2 bar)
    - Phase 2: spray activation (3549s - 6548s)
    - Phase 3: (500s) steam+helium injection (1500 s) (4052s – 5563s)

Fig. 7. Test conditions of SS1

3.2 SS1 Test Results

Fig. 8 shows the pressure change inside the SPARC. Looking at the pressure behavior, the pressure rises to about 2 bar while injecting steam at the condition of initial 1 bar of pure air. In addition, the pressure drops slightly as the spray operates, but the pressure rises again by the steam and helium injection in phase 3. It can be seen that after stopping the injection of steam and helium, the pressure inside the SPARC decreases again by spray.

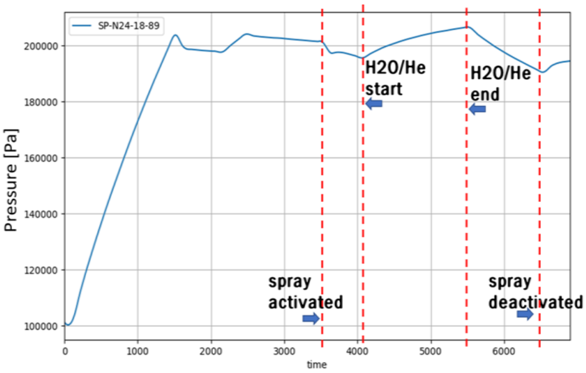


Fig. 8. Temporal pressure behavior for the SS1 test

Fig. 9 shows the temperature change over time measured by thermocouples installed on the center line of the SPARC. It can be seen that the gas temperatures decreased rapidly by about 10 degrees or more as the spray was activated. As steam and helium are injected, the temperature near the nozzle rises, so it can be assumed that the gas injected at about 120°C (here, a mixture gas of helium and steam) does not diffuse completely.

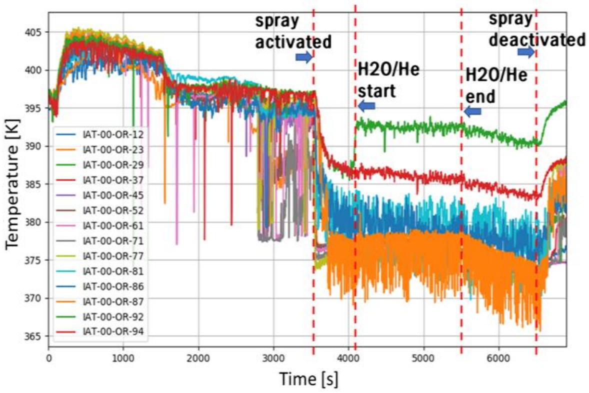


Fig. 9. Temperature distribution along time for the SS1 test

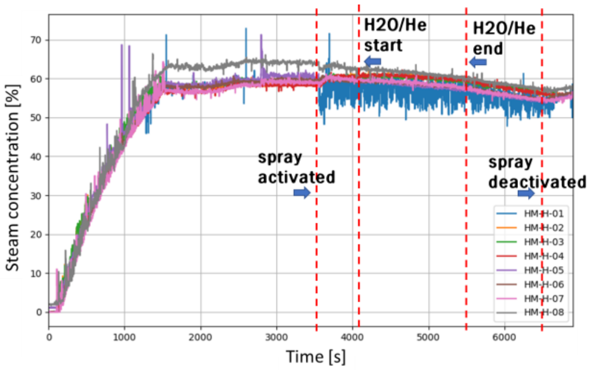


Fig. 10. Steam distribution along time for the SS1 test

Fig. 10 shows change of the steam concentrations over time in SS1 test. It depicts that the steam concentrations slowly decrease even in the period of the steam and helium injection by the spray operation.

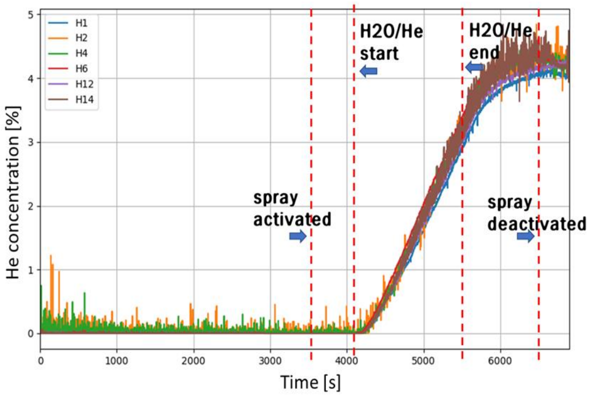


Fig. 11. Helium distribution along time for the SS1 test

Fig. 11 shows the distribution of helium concentration in the SS1test and has a nearly uniform distribution of helium inside the test vessel. This is considered to be the result of the increase in the mixing of helium due to the decrease in buoyancy caused by spray, the generation of steam condensate particles, and the mixing flow of gas induced by the frictional force of the spray droplets. Another unusual phenomenon is that the concentration of helium continues to increase even after the injection of steam and helium is stopped. From this, it can be assumed that the helium concentrations after the helium injection was stopped were relatively increased by condensation of the steam.

4. Heat-Sink Experiment

The SH (SPARC-HEATSINK) experiment is an experiment that evaluates the effect on the distribution of hydrogen when the heat sink is operated while hydrogen is being released, and evaluates the change in hydrogen concentration and mixing characteristics due to steam condensation during the heat sink operation. In the SPARC experiment, helium was used instead of hydrogen for safety considerations, and a mixture of steam and helium was injected for the SH tests.

4.1 SH1 Test Conditions

The main purpose of the SH1 experiment was to simulate the behavior of hydrogen during heat sink operation. The test procedure is first to raise the temperature of the SPARC pressure vessel to about 120 °C, to close the SPARC pressure relief valve, to inject steam, and to raise the pressure to 2 bar. Under this condition, a rest period was left for a while to remove internal turbulence disturbance, and then a heat sink was activated. Then, after 500 seconds, the behavior of helium was measured by injecting steam and helium in a mixed condition under the condition that the heat sink was operated. Fig. 12 shows the design conditions of the SH1 experiment.

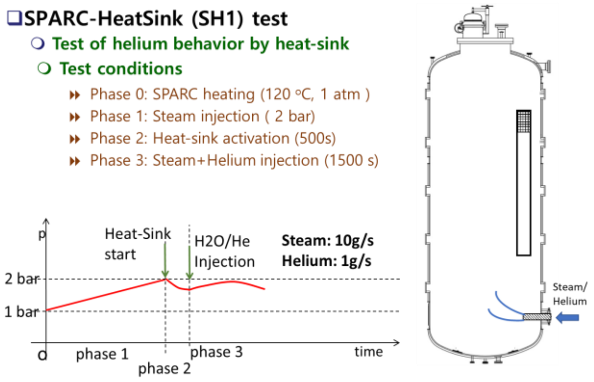

❑SPARC-HeatSink (SH1) test
- ○ Test of helium behavior by heat-sink
  - ○ Test conditions
    - ⏩ Phase 0: SPARC heating (120 °C, 1 atm)
    - ⏩ Phase 1: Steam injection (2 bar)
    - ⏩ Phase 2: Heat-sink activation (500s)
    - ⏩ Phase 3: Steam+Helium injection (1500 s)

Fig. 12. Test conditions of SH1

4.2 SH1 Test Results

Fig. 13 shows the pressure change inside the SPARC pressure vessel in the SH1 experiment.

The pressure quickly decreases after the heat sink is activated. But the inclination of the pressure drop tends to decrease very much when steam and helium are injected. The pressure is quickly lowering again after stopping the injection of water vapor and helium.

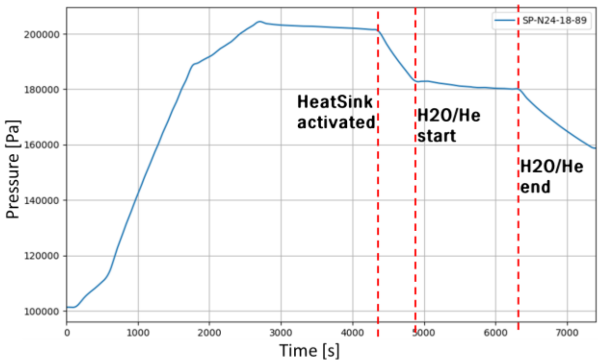


Fig. 13. Temporal pressure behavior for the SH1 test

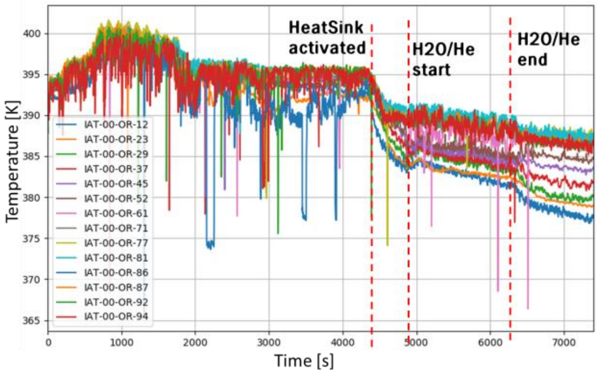


Fig. 14. Temperature distribution along time for the SH1 test

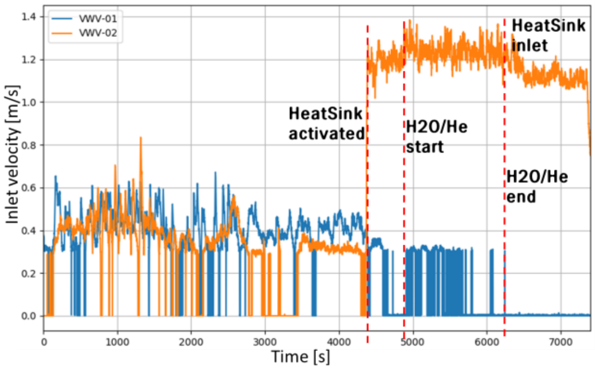


Fig. 15. Inlet velocity of the heat-sink for the SH1 test.

During the phase 1 of the SH1 experiment, a strong turbulent flow was generated in SPARC by the steam injection and pressurization of the vessel. Very irregular velocities of about 0.4 m/s were measured by the vane wheel velocity-meter installed at the inlet of the heat sink. However, it can be seen in Fig. 15 that the natural circulation flow occurs in the heat sink chamber while the heat-sink is operating.

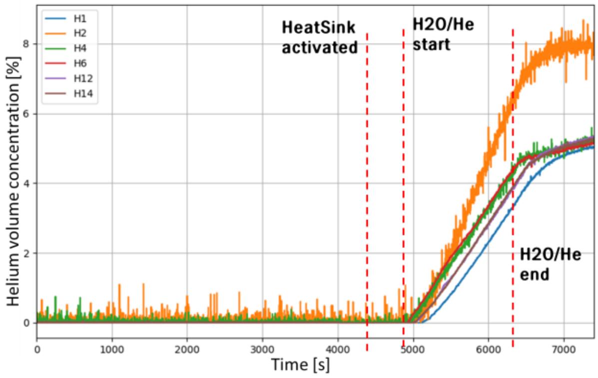


Fig. 16. Helium distribution along time for the SH1 test

Fig. 16 shows the concentration distribution of helium inside SPARC in the SH1 experiment. The helium concentration at the measuring point of H2 which is located between the heat-sink outlet and the steam-helium injection nozzle is highest compared to other locations all the time after the mixture gas of the steam and helium starts to be injected. In the case of the SH1 experiment, it is expected that the buoyancy which is a driving force for upward flow of the injected steam and helium is lost as the injected mixture gas and the cooled gas through the heat sink are mixed while the heat sink is operating.

5. Conclusions

Experiments on the operation of spray under hydrogen release conditions using helium confirmed that the mixing of hydrogen induced by spray droplets behavior is more dominant than decrease of steam concentration by its condensation which may increase a local hydrogen concentration.

It was confirmed from the heat-sink experiment SH1 that the downward flow of the cooled air is formed by the heat sink operation and it may occur that hydrogen may be accumulated in the lower part during hydrogen injection. As a future work, it is planned to study optimal control of a spray system for an accident management including hydrogen mitigation.

ACKNOWLEDGMENTS

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