Evaluation of PAR Hydrogen Recombination Characteristics Using Experimental Results from SPARC PAR Tests SP8 and SP9

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1. Introduction

Recently passive auto-catalytic recombiners (PARs) are commonly used to mitigate a hydrogen hazard in severe accidents of a nuclear power plant (NPP) because of their passive nature. Along with installation of the hydrogen mitigation system (HMS) in the containment, it is required to show the effectiveness of the system.

In order to apply the CFD approach to the hydrogen safety analysis, validated models for HMS are required to be implemented, which also require qualified experimental data.

The THAI project [1], organized by OECD/NEA and carried out by Becker, Germany, has conducted various experiments on PAR. The HR (hydrogen recombination) test of the THAI project evaluates the hydrogen removal characteristics of PARs under various thermal hydraulic conditions. In the first phase of the THAI project, THAI-1, 30 experiments were conducted using three types of PARs, AREVA, NIS, and AECL. But currently, there are very few published experimental data using grid (honeycomb) type PARs manufactured by domestic companies, which are installed in the Korean NPPs.

The first step to evaluate hydrogen safety and effectiveness of the HMS installed in a NPP containment is to obtain qualified test data of the HMS for validation of its analytical model.

Recently SPARC PAR tests of SP8 and SP9 [2] were conducted to evaluate hydrogen recombination characteristics of a grid-type PAR as a function of initial hydrogen concentration. In the tests, the hydrogen concentration was uniformly distributed to minimize the effects of the hydrogen jet flow from the injection nozzle.

This study focuses on the evaluation of the hydrogen recombination using experimental results from the SPARC PAR tests SP8 and SP9 [2], expecting that the test data would be used for validation of analytical models and numerical codes [3].

2. Analysis of Experimental Data

In the THAI project [1], Kanzleiter et al. applied two different methods for evaluating hydrogen removal rates. The first method (Method-1) is based on the mass flow rate of hydrogen at the inlet and outlet of the PAR duct, as in the channel experiment, and the second method (Method-2) uses the difference between the injected hydrogen and the remaining hydrogen inventory in the vessel.

Method-1 and Method-2 have different drawbacks, depending on assumptions applied. Method-1 is based on a steady or quasi-steady state assumption. Also, it uses an assumption of uniform inlet profiles of gas properties because of limited number of the installed probes. In method-2 hydrogen mass inventory in a test vessel, which is crucial for a hydrogen removal rate, is obtained by integrating hydrogen concentrations measured with limited number of probes. Therefore, to reduce the mass error, the gradient of hydrogen concentration should be minimized or the number of probes should be increased.

When hydrogen is injected into the test vessel, the hydrogen gradually diffuses to the surface of the PAR catalyst body, and the catalyst reaction starts, and the catalyst body and the exhaust gas are heated by the exothermal catalytic reaction. The heated exhaust gas exits the catalyst body by buoyancy, and the PAR operates continuously by the chimney effect that induces the inflow of new gas into the lower part of the PAR. It is difficult to obtain a uniform distribution of hydrogen in the test vessel because of hydrogen injection and exhaust gas release of a PAR.

SPARC-PAR tests SP8 and SP9 were performed to compare Method-1 and Method-2 under uniform hydrogen distribution conditions. For a uniform hydrogen distribution in the vessel before the PAR operation, a flat gate was installed at the inlet of the PAR.

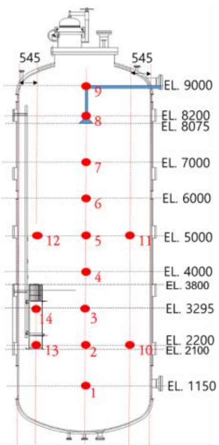

Fig. 1. SPARC test vessel and measurement locations.

The experiment was performed by adjusting the average hydrogen concentration before opening the PAR gate to 4% (SP8) and 6% (SP9). The conditions of the SPARC-PAR experiment were as follows.

- SPARC initial conditions: 1.46 bar, 50 ºC
- SP8: nominal hydrogen concentration is 4%, the total amount of injection is about 343 g.
- SP9: nominal hydrogen concentration is 6%, the total amount of injection is about 508 g.

Fig. 1 schematically shows the SPARC-PAR test vessel and locations of measurement for gas concentration and temperature.

The SP8 test is an experiment in which the gate of PAR is opened at a uniform hydrogen concentration of 4%. Hydrogen was injected at a flow rate of 0.6 g/s, and a fan was operated to mix hydrogen after the first injection. During the fan operation, hydrogen was additionally injected, and when the hydrogen concentration value in the test vessel reached 4%, the hydrogen injection and fan operation were stopped, and the PAR gate was opened at 3380 seconds.

Fig. 2 shows the hydrogen concentration distribution along the center line of the SPARC pressure vessel. After the fan for hydrogen mixing stops, it can be seen that the hydrogen concentration is uniformly distributed at 4%.

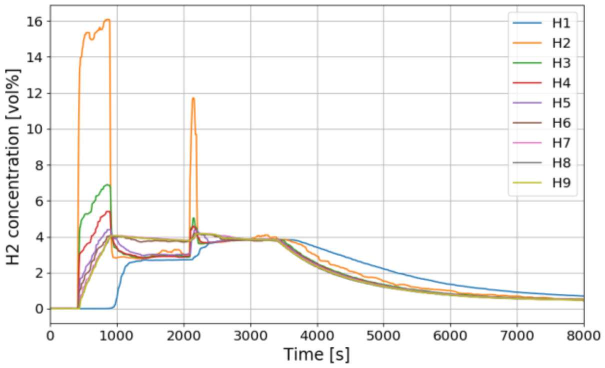

Fig. 2. Hydrogen distribution along the center line of the SPARC vessel for the SP8 test.

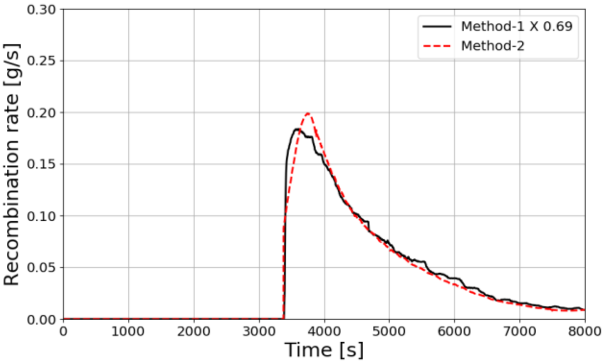

Fig. 3 Recombination rates by Method-1×0.69 and Method-2 for SP8 test.

The recombined hydrogen mass by the KNT KPAR40 PAR can be calculated using Method-1 and Method-2. A correction factor was introduced to equalize the recombined mass from method-1 to Method-2. Its value was determined by Eq. (1).

$$\phi_{corr} = \frac{m_{H2,init} - m_{H2,final}}{\int R_{rec,Method-1}} \quad (1)$$

The hydrogen removal rates using the SP8 test data are shown in Fig. 3. It depicts that the Method-1 result multiplied by the correction factor ϕ_{corr} is very similar to the removal rate by Method-2.

The SP9 test was conducted to evaluate the PAR recombination characteristics at the higher hydrogen concentration that the SP8 test by injecting about 500 g of hydrogen into the test vessel.

Fig. 4 shows the hydrogen concentration distribution at the centerline of the test vessel in the SP9 test. It can be seen that the concentration gradient of hydrogen is very large during the hydrogen injection period. In SP9, the gate of PAR was opened at 1940 seconds, and at this time, the hydrogen concentration showed a very uniform concentration distribution at about 5.5%.

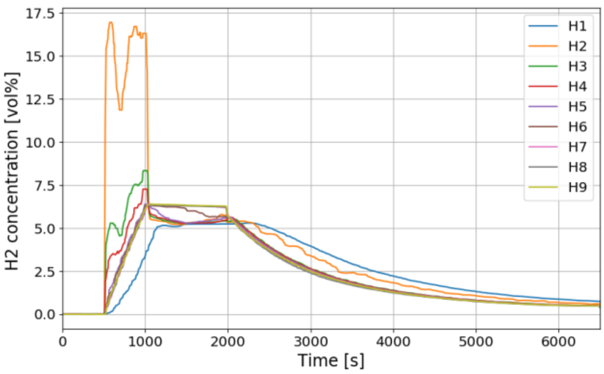

Fig. 4. Hydrogen distribution along the center line of the SPARC vessel for the SP9 test.

3. CFD Simulation of the Tests

The SPARC-PAR tests SP8 and SP9 were simulated to evaluate PAR hydrogen recombination Characteristics by comparing with the experimental results.

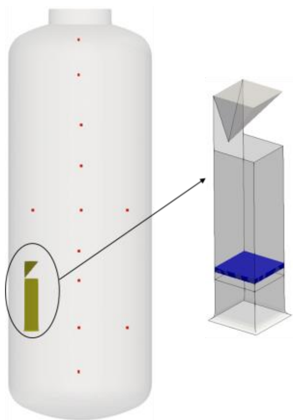

Fig. 5. Geometry modeling for CFD simulation of the SAPRC-PAR tests SP8 and SP9.

KNT KPAR40 with a skirt installed at the bottom of the PAR chamber was geometrically modeled by a thermal baffle approximation as shown in Fig. 5.

In this study, bulk and wall condensation were considered with time-varying temperature on the vessel wall, which were measure during the tests. The simulations were performed by setting the test conditions at the time of PAR gate opening as initial conditions.

Fig. 6 shows the hydrogen distributions along time after PAR recombination initiated. The hydrogen concentration is higher in the lower plenum region of the vessel than the upper region. It is because that the heated exhaust gas from the PAR moves upward by buoyancy and is accumulated at the upper region.

The hydrogen mass in the vessel is slowly reduced by the PAR recombination. The behavior of the hydrogen inventory in the test vessel is well predicted as shown in Fig. 7.

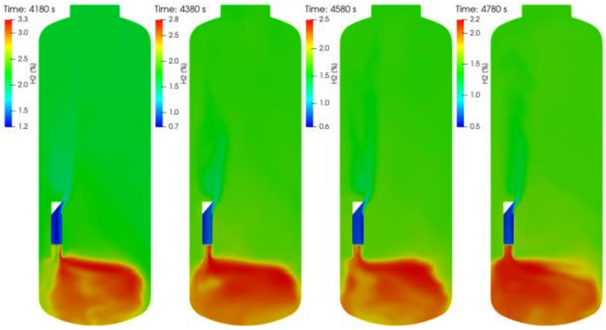

Fig. 6. Hydrogen distributions at 4180s, 4380s, 4580s, and 4780s from the SP8 test simulation.

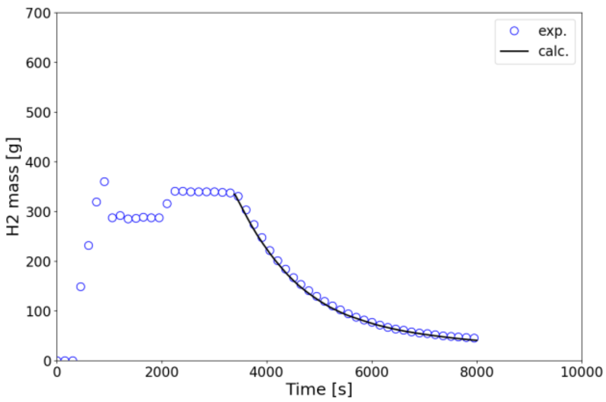

Fig. 7. Comparison of the hydrogen mass remaining in the vessel.

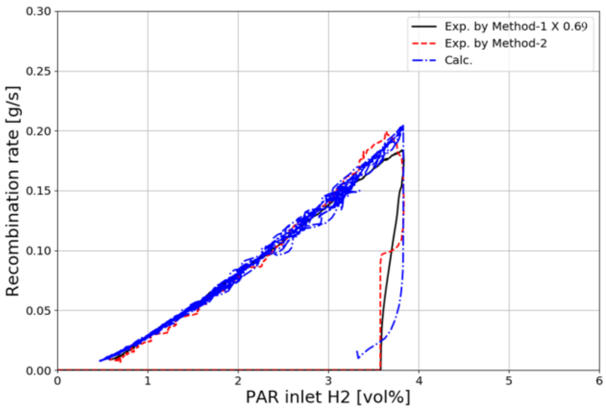

Fig. 8. Comparison of the PAR recombination rates dependent on inlet hydrogen concentration.

One of the most important characteristics of the PAR recombination is its dependency on the inlet hydrogen concentration because PAR performance of hydrogen mitigation is applied for a hydrogen safety analysis in a NPP containment as function of PAR inlet conditions such as the hydrogen concentration.

Fig. 8 shows a comparison of the PAR recombination rates as a function of inlet hydrogen concentration. The recombination rates from the PAR model used in this study agree very well with those evaluated by Method-2. They also agree well with the Method-1 results multiplied by the correction factor. It means that the correction factor is necessary for the recombination rates by Method-1.

The SP9 test was also simulated by the same approach used for the SP8 test simulation. But the initial and boundary conditions for the simulation were set with the SP9 test conditions, in which hydrogen concentration in the test vessel before PAR gate opening is higher than the SP8 test.

The behaviors of the heated gas released from the PAR can be observed from the temperature distributions in the test vessel. Fig. 9 shows the temperature distributions at some time steps after the PAR operation initiation. It is seen that a positive temperature gradient is developed in the test vessel by the heated exhaust gas.

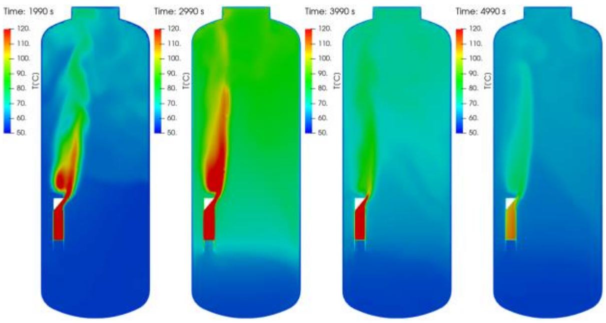

Fig. 9. Temperature distributions at 1990s, 2990s, 3990s, and 4990s from the SP9 test simulation.

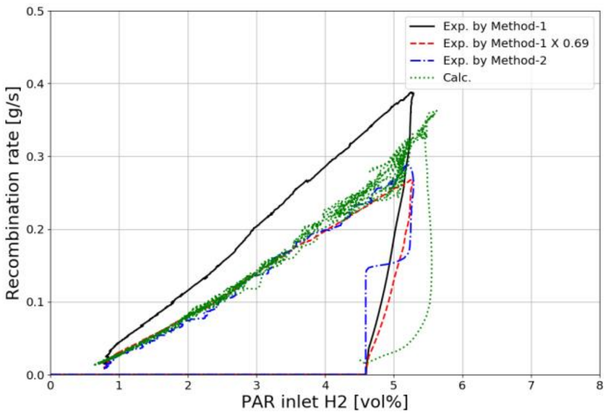

Fig. 10. Comparison of the PAR recombination rates dependent on inlet hydrogen concentration.

Fig. 10 shows a comparison of the PAR recombination rates as a function of inlet hydrogen concentration for the

SP9 test. The recombination rates from the SP9 test simulation agree very well with those evaluated by Method-1 when the correction factor was considered.

4. Conclusions

In this study, PAR hydrogen recombination characteristics were evaluated using the experimental data from SPARC PAR Tests SP8 and SP9, where a small-sized KNT PAR KPAR40 was used. Two methods, Method-1 and Method-2, with a CFD simulation were considered for calculating the hydrogen recombination rates. It was confirmed that the recombination rates from Method-1 requires a correction factor to be compatible with results from Method-2 and the CFD method.

ACKNOWLEDGMENTS

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