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Research on a Hydrogen Stratification Induced by PARs Installed in a Containment

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1. Introduction

In order to remove a hazard of hydrogen explosion in a nuclear power plant (NPP) containment during a severe accident, it is required to have a hydrogen mitigation system (HMS) installed in the containment. Among hydrogen mitigation devices, passive auto-catalytic recombiners (PAR) are commonly used in nuclear reactor containments because of its passive hydrogen depletion characteristic.

Along with installation of the HMS in the containment, it is also required to show the effectiveness of the system. For many years, the hydrogen safety analysis has been done by using a lumped-parameter (LP) analysis code. But because a LP code relies on a very coarse mesh such as dozens of control volumes (CV) for a whole containment volume, it is difficult to resolve gradients of properties like a hydrogen concentration. So, it is thought that the lumped-parameter code has a limitation in predicting the three-dimensional behavior of hydrogen transport and mixing within a full containment. Even by a 3-dimensional detail analysis code, it is still challenging to realistically simulate hydrogen behaviors in a containment during a severe accident. So, it is needed to make efforts for best-estimate analyses by validating analytical models with appropriate experimental data

A hydrogen stratification phenomenon may occur in a containment by many reasons. Among them, PAR-induced hydrogen stratification was mentioned at PARIS-I in the frame of SARNET WP12-2 [1] containment atmosphere mixing. In this case, hydrogen can be accumulated in a lower region because a lighter exhaust gas of PARs occupying an upper region hinders an upward flow of the hydrogen.

Currently it is underway to set up the SPARC test facility for an experimental simulation of hydrogen stratification phenomenon affected by PAR or PARs activation [2]. In parallel to the experimental study, an analytical study for a numerical simulation of the hydrogen stratification induced by PARs are being conducted.

In this study, the h2RecombinerFoam [3] code was implemented to evaluate thermal hydraulic behavior of hydrogen especially hydrogen stratification induced by activation of PARs. And, a single volume lumped-parameter analysis code has been developed and used to quantitatively evaluate the effect of hydrogen stratification on a global hydrogen depletion rate in a containment in a conservative point of view of hydrogen safety.

2. Modeling and Results

In this section analytical models used to simulate hydrogen behaviors with PAR's recombination are described. And results from its application to pre-test calculation of the SPARC-PAR experiment and the SMART containment are presented.

2.1 3-dimensional analysis model

Multi-component compressible Navier-Stokes equations for conservations of mass, momentum, energy and species masses are used as governing equations.

In order to resolve turbulence mixing of gas, a 2-equation turbulence model with buoyancy effect is considered. Chemical reactions in a PAR is modeling by a global 1-step reaction mechanism with a PAR vender-supplied hydrogen depletion rate.

2.2 Lumped analysis model

A single volume lumped analysis code, parVol, has been developed to evaluate a hydrogen depletion characteristic by PARs installed in a containment. The code is composed of 2 program modules. One is for calculation of mass and energy evolutions with thermal properties of gas species. The other module is designed for calculation of hydrogen removal rates from commercially-available PARs such as AREVA, NIS, AECL, KNT and CERACOM. A hydrogen mass rate released into a containment can be imported as a file into the code. With the hydrogen mass source equations for conservations of mass and energy of a gas mixture are solved every time step. Heat loss to a containment wall is modeled by assuming a natural convective heat transfer.

2.3 Pre-test analysis of SPARC-PAR experiment

In the SPARC-PAR experiment, two KNT small PAR, KPAR40, are installed at an elevation of 6 m from the bottom of the SPARC vessel. As a test condition, hydrogen is released during 1,000s at a rate of 0.26 g/s through a vertical pipe with a diameter of 0.3 m.

A numerical simulation using h2RecombinerFoam has been conducted as a pre-test calculation. Fig. 1 shows hydrogen distributions at different times.

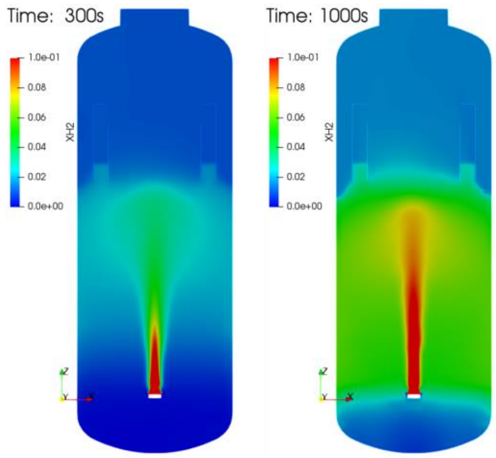

Fig. 1. Pre-test calculation of a SPARC-PAR experiment

It is shown that the buoyant jet of the hydrogen is not penetrating gas cloud in the upper region of the vessel by the lighter density of the exhaust gas of the PARs.

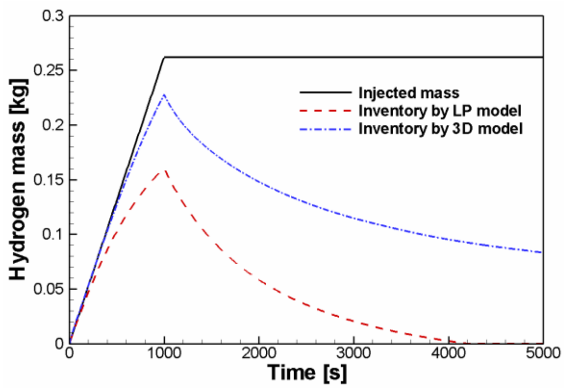

Fig. 2. Comparison of hydrogen mass inventories along time in the SPARC vessel

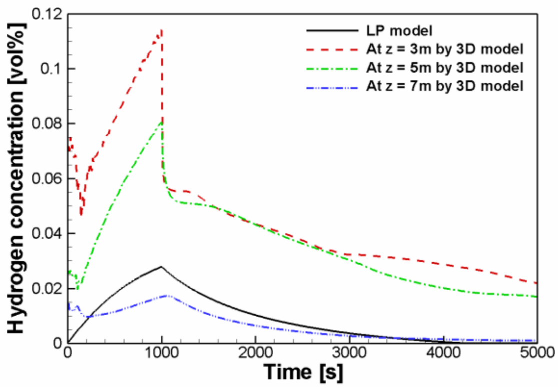

Fig. 3. Comparison of hydrogen concentrations along time in the SPARC vessel

In Fig. 2 hydrogen mass inventories from the parVol and h2RecombinerFoam codes are compared along time. The result of the lumped code shows that all the hydrogen injected into the SPARC vessel during 1000s is removed after 4000s. On the contrary, there exists about 100 g of hydrogen in the vessel by the 3D analysis code. This discrepancy is mostly caused by hydrogen stratification unresolved by the lumped code. Fig. 3 shows hydrogen concentrations in the vessel along time. The distribution of the hydrogen concentrations from the h2RecombinerFoam code depicts that the hydrogen stratification is continuously maintained even after the hydrogen injection.

2.3 Hydrogen distribution in SMART

In order to evaluate hydrogen distribution and PAR performance in the SMART containment, 193 kg of hydrogen mass generated by 100% oxidation of the SMART fuel is used, which is obtained from linear extrapolation of a hydrogen release rate from a MELCOR analysis result. In the current design of SMART, hydrogen can be released through two vents of RRT pools

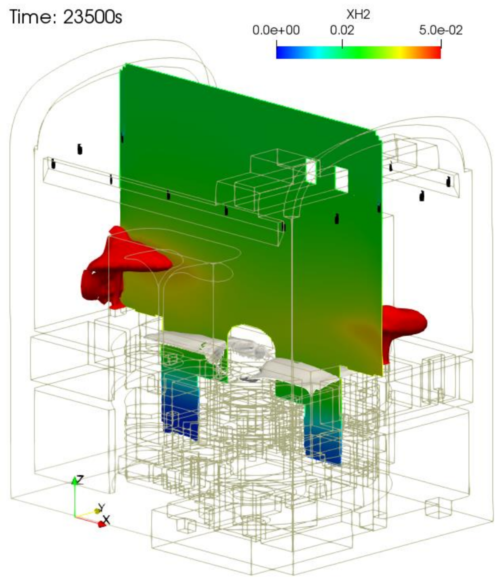

Fig. 4. Hydrogen distribution in the upper containment area of SMART at 23500s.

Fig. 4 shows the hydrogen distribution in the upper containment area of SMART at 23500s after the accident initiation. The hydrogen jet is not stretched upward and rather bent sideways. This looks like a stratification of hydrogen by PARs installed in the upper region of the containment.

Variations of hydrogen mass inventories along time are compared between the parVol and h2Recombiner-Foam codes in Fig. 5. The two codes give very similar results for the time when the hydrogen mass inventory reaches a maximum value. But during the hydrogen depletion period after 10000s, the two codes give a relative discrepancy in the depletion rates based on the total mass of the released hydrogen. It is thought that the difference is mostly from the hydrogen stratification induced by PARs installed in the containment.

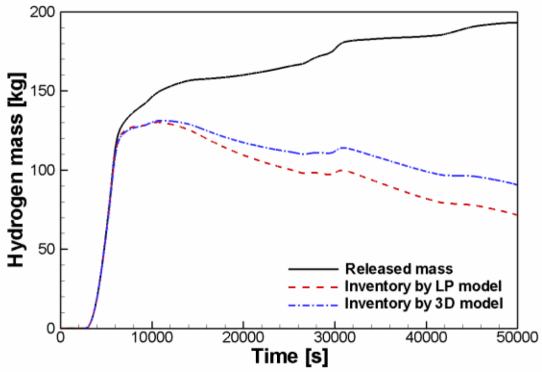

Fig. 5. Comparison of hydrogen mass inventories along time in the SMART upper containment

3. Conclusions

Simulation of hydrogen behaviors in a containment with PARs were conducted by using the h2RecombinerFoam code. The hydrogen depletion rate was compared with that from the single-volume lumped analysis. In order to validate analytical models in the code, it is planned to conduct an experiment of a PAR induced hydrogen stratification using the SPARC test facility

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