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# Hydrogen Behaviors Coupled with Thermal Hydraulics in APR1400 Containment during an SBLOCA

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## 1. Introduction

During a severe accident with a core damage in a water-cooled nuclear reactor, a large amount of steam and hydrogen is released into the reactor containment. If a highly-concentrated hydrogen mixture cloud is developed in a certain region of an NPP (nuclear power plant) containment, it is probable that hydrogen flame undergoes DDT (deflagration to detonation transition) locally or globally in the containment, which may threaten the integrity of the containment. There are two hydrogen mitigation strategies. One is burning hydrogen by igniters as it is released in the containment. The other is using PARs (passive auto-catalytic recombiners) to remove the hydrogen. The strategy based on PAR installation requires well-mixing of the released hydrogen with steam in a containment atmosphere. It means that hydrogen distribution in a containment is very important for the hydrogen mitigation by PAR.

Hydrogen behaviors in a NPP containment is strongly coupled with thermal hydraulics such as turbulent mixing, stratification by buoyancy, steam condensation, heat transfer et al. The purpose of this study is to investigate hydrogen behaviors in the APR1400 containment during an SBLOCA with a reactor core damage. The GASFLOW [1] code is used to simulate hydrogen behaviors with thermal hydraulics in the APR1400 containment.

## 2. Analysis Results

### *2.1 Physical Models for hydrogen safety analysis*

Hydrogen behaviors in an NPP containment during a severe accident are strongly coupled with thermal hydraulics in the containment. Important thermal hydraulic physics which must be considered are buoyant jet flow, turbulent mixing, gas species diffusion by concentration gradients, steam condensation, thermal radiation, structure heat transfer et al. [2],

The GASFLOW code models the two-phase effects of condensation and/or vaporization on a fluid mixture by an assumption of the homogeneous equilibrium model (HEM). Steam and hydrogen are release as a jet flow continuously or intermittently depending on an accident progression. The jet flow delivers mass and energy of steam and hydrogen from a RCS (reactor cooling system) to a containment. A momentum of the flow has a crucial role in mixing of the gases with a containment atmosphere. The convective mixing is enhanced by a turbulence. For the current study, the standard k-e turbulence model was used to simulate a turbulent mixing by a buoyant jet flow released from a cold-leg break of APR1400. It is possible that copious amount of super-heated steam is released into the containment which reduces the concentration of the hydrogen distributed in the containment and it also acts as a thermal source. This thermal source can be transported not only by condensation and convection heat transfer but additionally by thermal radiation heat transfer. Steam is normally participating in thermal radiative heat transfer because of its large opacity. In this study, the radiative heat transfer was considered by solving a radiation equation with a P-1 spherical harmonic method which was implemented in the GASFLOW code.

### *2.2 SBLOCA Analysis*

#### *1) Hydrogen Source Modeling*

A severe accident scenario chosen in this study for a hydrogen behavior analysis is a SBLOCA in APR1400. Accident progression in the RCS of APR1400 is calculated by the MAAAP code [3]. The total amount of hydrogen generated in the reactor vessel during 10,000 s is 634kg.

Based on 10 CFR 50.44 [4], regulation of NRC for combustible gas control in a NPP containment, hydrogen from a fuel-clad coolant reaction involving 100% of the fuel cladding surrounding the active fuel region must be considered to evaluate a hydrogen safety in the containment. The maximum hydrogen mass from a full oxidation of the active core in APR1400 is around 1002 kg. It is probable to get a hydrogen generation from the full oxidation by a modified oxidation model in the MAAP code. In this study, a simple linear extrapolation of a hydrogen release rate from a MAAP analysis result is used to get the maximum hydrogen mass.

Fig. 1 shows the mass release rates of water, steam and hydrogen. The hydrogen release rate is multiplied by a certain factor to meet 100% oxidation of the active core of APR1400. The total hydrogen mass by integrating the release rate along time is about 1002 kg.

It is assumed that a break happens on a cold-leg of the RCS and the location of the break and a flow direction from the break is assumed as follows.

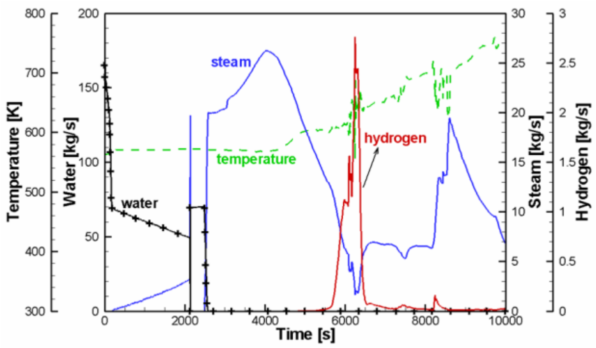



Fig. 1. Mass release rates of water, steam and hydrogen

Table 1 Break locations and flow directions for SBLOCA

| Break | Flow direction |
|---|---|
| Top | upFlow (upward flow) |
| Bottom | downFlow (downward flow) |
| Right side | cwFlow (clockwise flow) |
| Left side | ccwFlow (counter-clockwise flow) |

In this study 4 test cases of upFlow, downFlow, cwFlwo, and ccwFlow are simulated by using GASFLOW. Fig. 2 shows the flow directions of release jet in the APR1400 containment.

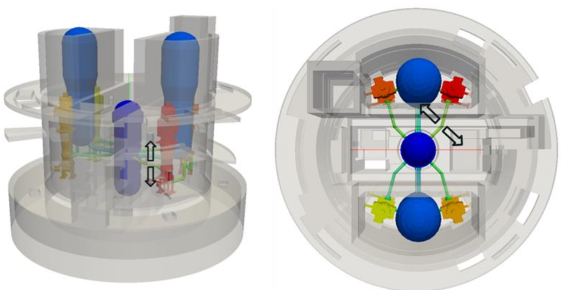
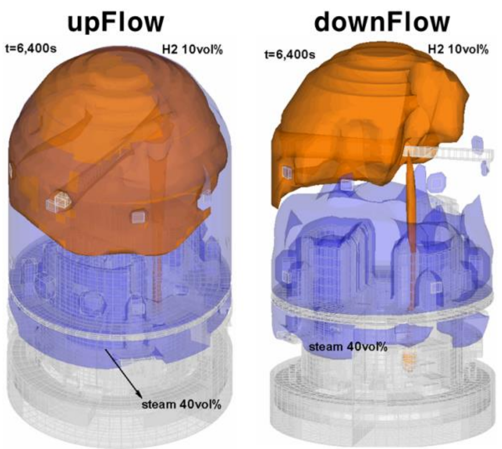


Fig. 2. Flow directions of release jet in the APR1400



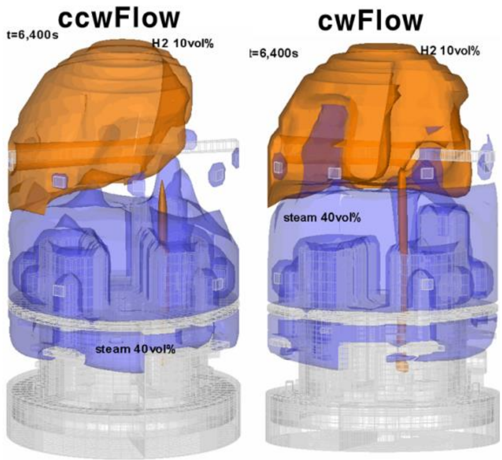




Fig. 3. Hydrogen and steam distributions visualized by iso-surfaces.

In Fig. 3 hydrogen and steam distributions are visualized by 10 vol% and 40 vol% iso-surfaces respectively at the time of maximum release rate of hydrogen (t = 6400s). A vertical jet of highly concentrated hydrogen is developed in a steam generator compartment with a cold-leg break. And a large cloud of hydrogen mixture with 10 vol% is shown in the dome region in all test cases. But a steam distribution in the containment is a little different among the cases. Especially in the upFlow case, 40 vol% steam cloud is spread up to the dome. In the other cases, the steam cloud is only shown in lower region surrounding upper steam generator compartment.

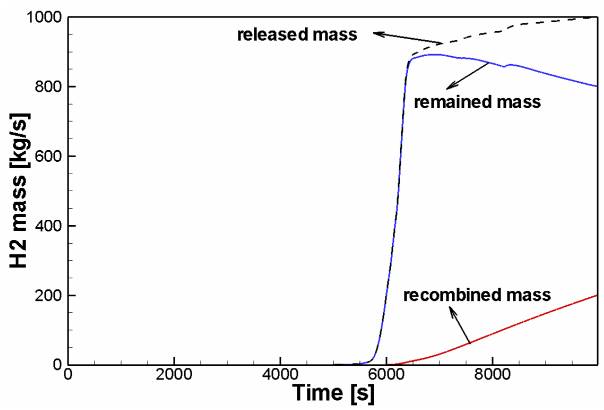



Fig. 4. Variation of hydrogen inventory in the containment for the upFlow case.

In Fig. 4 hydrogen remaining in the containment along time is shown. A total Hydrogen mass removed by recombination of PARs installed in the containment is shown in the figure. It must be noted that a recombination correlation of AREVA PAR is used in this study. During the first period of hydrogen release, the PARS are not active. After the released hydrogen is distributed in the dome region, the PARs start to operate.

In Fig. 5, hydrogen distributions in the containment at t = 6400s are visualized by contours on a vertical plane with the break point.

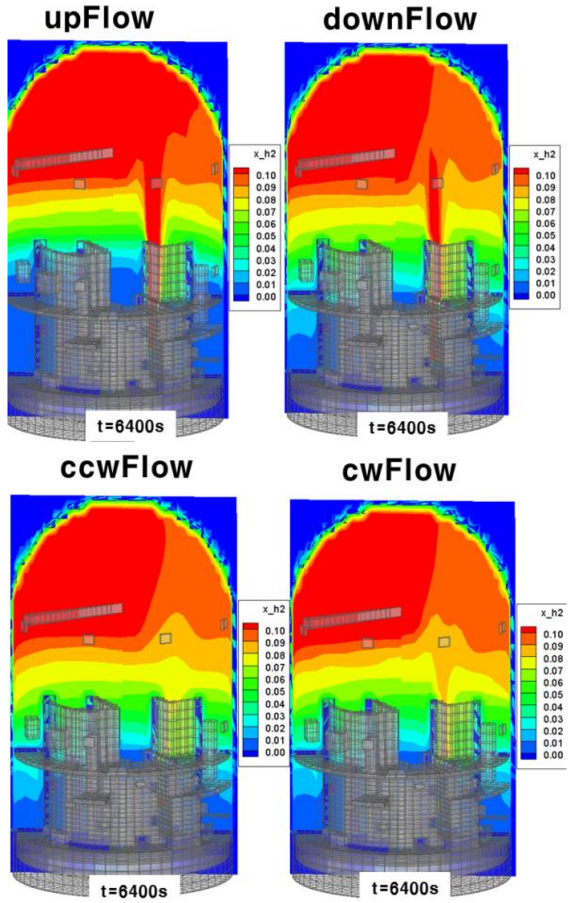
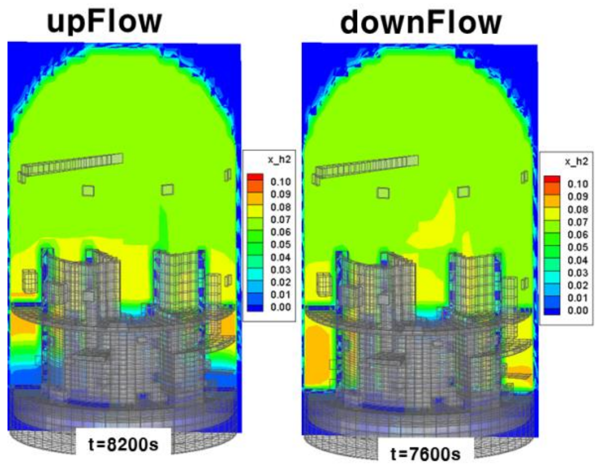



Fig. 5. Contours of hydrogen concentrations at t=6400s.

In the figure, it is found that most of the released hydrogen is distributed above the operating deck of the containment.



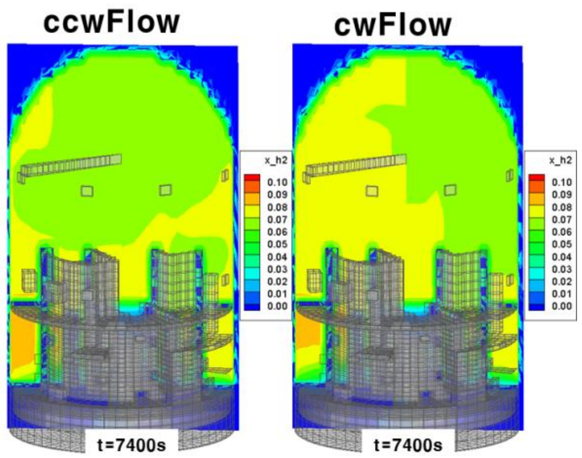




Fig. 6. Distributions of hydrogen after the period of high release rate.

Hydrogen distributions in the containment after the period of high release rate are compared for the 4 cases in Fig. 6. In all the cases, it is found that hydrogen mixture cloud with higher hydrogen concentration exits in the annular compartment below the operating deck. The hydrogen concentrations below the operating deck reach around 8 vol%. It is believed that the hydrogen distribution is strongly affected by thermal hydraulics in the containment. The first reason of the hydrogen dilution in the upper containment is mixing with steam released after 7000s. It is seen that the jet flow of the super-heated steam penetrates the hydrogen mixture cloud developed in the dome region by buoyancy and expels the hydrogen mixture cloud downward.

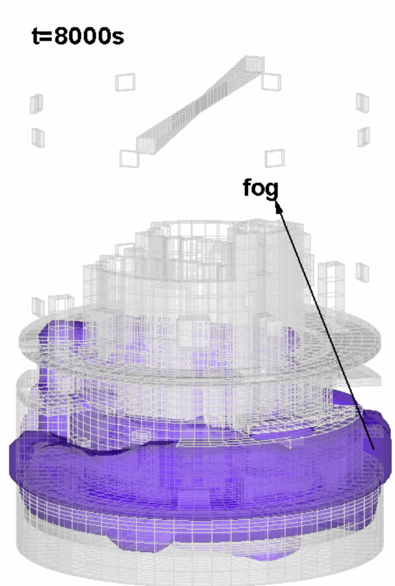



Fig. 7. Distribution of fog in the containment

The hydrogen and steam mixture cloud initially created in the dome region slows cools down and fog may be generated by condensation of steam included in the cloud during the downward movement. The fog contained in the cloud makes its density increased and hydrogen more concentrated. Fig. 7 shows a distribution of fog in the case of upflow. Most of fog from steam condensation exits in the lower part of the containment.

It is understood from this study that steam condensation has an important role in the hydrogen distribution in the containment.

In order to see amount of hydrogen distributed in the annular compartment, the hydrogen concentration without steam is visualized in a horizontal plane. In fig. 8, it is seen the hydrogen concentration is considerably increased when the steam contained in the mixture cloud is removed.

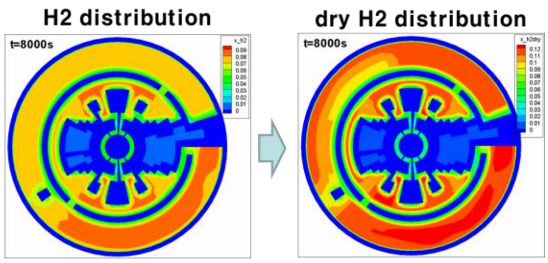



Fig. 8. Left: distribution of hydrogen with steam, right: dry hydrogen

It must be noted that gratings and pipings installed in the annular compartment are not considered in the GASFLOW input model used in this study.

## 3. Summary

In this paper, the hydrogen behaviors in the APR1400 containment during an SBLOCA were investigated by numerical simulation using GASFLOW. It was found that hydrogen mixture cloud may move downward relying on thermal hydraulic effect occurring in the containment.

It is thought that condensation of steam included in the hydrogen mixture is very important in the hydrogen behaviors.

## ACKNOWLEDGMENTS

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