Methodology for Evaluation of Hydrogen Safety in a NPP Containment

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1. Introduction

During a severe accident with a core degradation in a nuclear power plant (NPP), it is required that hydrogen concentration in a compartment of the NPP must be maintained below a detonable limit even in the case of 100% fuel cladding oxidation in view of equipment survivability. And a free volume of a NPP containment must be large enough to prohibit an occurrence of a containment-wise global detonation by limiting global averaged hydrogen concentration below 10 vol%.

In the frame of a technology development to evaluate accident management strategy for containment hydrogen mitigation, it is on-going to develop an analytical tool, containmentFOAM, for a turbulence-resolved detail analysis of hydrogen behaviors in a NPP containment based on OpenFOAM [1]. It is composed of h2MixingFoam for turbulent mixing of hydrogen with steam condensation, h2RecombinerFoam for PAR performance evaluation, h2FlameFoam for turbulent hydrogen combustion, and h2SprayFoam for spray effect on hydrogen behaviors. As such, containmentFOAM is designed to be modular in order to overcome numerical problems from length and time scales. A time period of hydrogen release to a NPP containment during a severe accident is in the order of 10,000 s, but the time scale to resolve turbulent flame propagation by hydrogen combustion is below 1 s. And the time scale is directly coupled with length scales. So the development of the analysis codes based on modular structure gives benefits in managing and using the codes. In the object-oriented modular libraries, physical models required for a simulation can be chosen at run-time and the model objects are constructed at that time.

In this study, containmentFOAM is applied for an evaluation of hydrogen safety in a preliminary design of a SMART containment.

2. Methods and Results

In this section, a methodology for evaluation of hydrogen safety in a NPP containment is introduced and the results from applying the methodology to a preliminary design of a SMART containment are presented.

2.1 Hydrogen safety evaluation methodology

It is difficult to evaluate a hydrogen safety in a NPP containment in a single step because of wide spectrum of time and length scales of hydrogen behaviors. Instead, multi-step approach is commonly used in the hydrogen safety evaluation. As a first step, hydrogen distribution in a containment is simulated during a period of hydrogen release. During the period, buoyant jet is mostly a dominant flow regime for hydrogen behaviors. If it is found that there exists a compartment in the containment with higher probability of hydrogen flame acceleration, an analysis of hydrogen combustion must be applied as a second step. Normally, sigma index as a flame acceleration criterion is used but a hydrogen concentration of 10 vol% in dry condition is a solid criterion for the flame acceleration. In order for the simulation of hydrogen distributions in a NPP containment, h2MixingFoam is under development and validation in the frame of containmentFOAM. An applicability test of the code to a real NPP containment has been conducted as shown in Fig. 2, where hydrogen distributions along time in an OPR1000 containment are depicted.

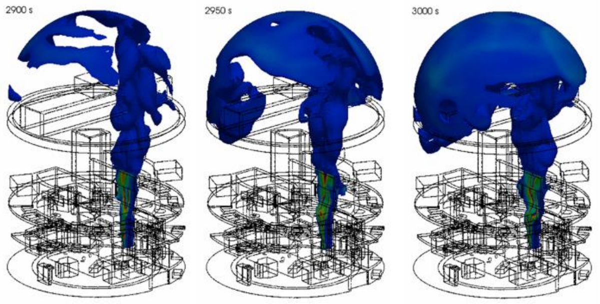

Fig. 1. Hydrogen distribution in an OPR1000 containment simulated by h2MixingFoam

Development of a hydrogen flame is such a complicated phenomena that turbulence, pressure wave and chemistry are all important. In view of the hydrogen safety, the occurrence of DDT (deflagration-to-detonation-transition) is most concerning because it can apply very high pressure load on a compartment structure. Unfortunately a direct simulation of DDT is technically impractical in a compartment scale. So a multi-step approach separated by a flame propagation regime is commonly used for a hydrogen safety in a large NPP containment. Fig. 2 depicts multiple regimes of a flame propagation to show a development of detonation.

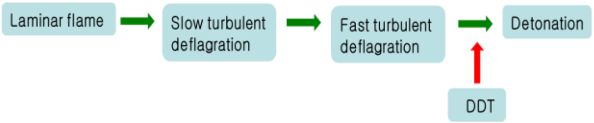

Fig. 2. Development of hydrogen flame

In a compartment scale, transition from a laminar flame to turbulent flame is inevitable. So, it is probable to neglect a simulation of laminar flame propagation by increasing an ignition zone. A flame acceleration is a prerequisite for DDT so that a lot of efforts have been made to develop models and codes for simulation of turbulent flame acceleration.

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2.2 Evaluation of hydrogen behaviors in SMART

Hydrogen distribution in the preliminary design of the SMART containment was simulated with a simple linear extrapolation of a hydrogen release rate from a MELCOR analysis.

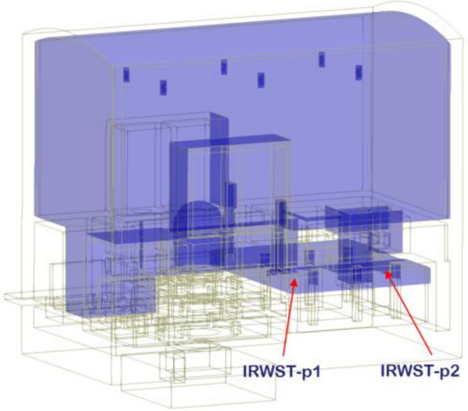

Fig. 3. Containment modeling and sampling points in the IRWST

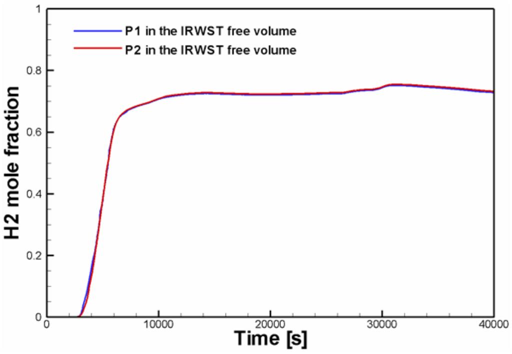

Fig. 4. Time variations of hydrogen concentrations at the sampling points

It was found that hydrogen concentration in the upper containment area is around 4 vol% but hydrogen is highly accumulated in the IRWST free volume as shown in Fig. 4. In the IRWST, hydrogen concentration continuously increases during 3,000 s. A hydrogen combustion is possible to happen at any time in the period. In order to evaluate characteristic of the hydrogen flame propagation in the IRWST free volume, hydrogen combustion was simulated with assumptions that hydrogen is fully mixed with air at stoichiometric condition (30 vol% of hydrogen) and the steam released from the reactor is fully condensed in the IRWST water. In the IRWST, as shown in Fig. 5, ignition is assumed to occur at far away from the vent ducts.

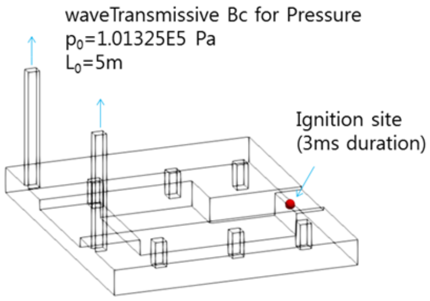

Fig. 5. Geometric mode of the IRWST and ignition location

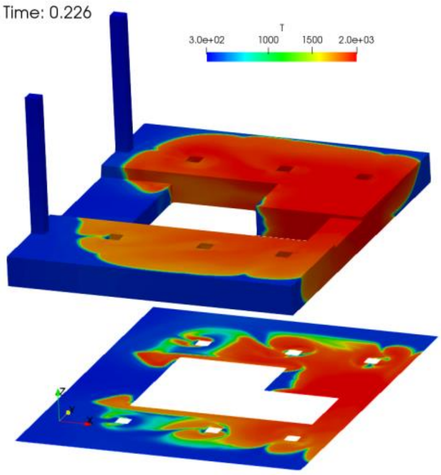

Fig. 6. Flame front in the IRWST at 0.226 s after ignition

Fig. 6 shows a flame front by temperature contours at 0.226 s after ignition. It is clearly shown that the hydrogen flame is very folded and stretched by internal structures. Flame speed was evaluated from the simulation results and it was found that maximum flame speed reaches 1,000 m/s near vent duct, which means that a possibility of DDT cannot be excluded.

3. Conclusions

From the evaluation of the hydrogen safety in the preliminary design of the SMART containment, it was found that a possibility of DDT cannot be excluded in the IRWST.

ACKNOWLEDGMENTS

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