Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 29-30, 2014

Multi-dimensional Analysis Method of Hydrogen Combustion in the Containment of a Nuclear Power Plant

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1. Introduction

During a core melt accident in a nuclear power plant (NPP), a large amount of hydrogen can be generated in a nuclear reactor and released into the reactor containment. Hydrogen combustion can occur in the containment when the concentration is higher than a flammability limit. During propagation of the hydrogen flame, it can be accelerated by interaction with a generated turbulence. The most severe case is the occurrence of detonation, which induces a few-fold greater pressure load on the containment wall than a deflagration flame. The occurrence of a containment-wise global detonation is prohibited by a national regulation. However, there is a possibility of compartment-wise local detonation. During the hydrogen release period, a gas mixture cloud containing highly concentrated hydrogen flows from a release location by a jet momentum and moves upward by buoyancy force. The compartments located in the flow path such as steam generator compartment, annular compartment, and dome region are likely to have highly-concentrated hydrogen. During a mixing period, which is a time after the hydrogen release period, the behavior of the hydrogen mixture cloud is very complicated by a release of steam following the hydrogen release, volumetric and wall condensation of steam, hydrogen recombination by PAR, and spray activation. Thus, it is important to accurately predict the possibility of hydrogen accumulation during the hydrogen release and mixing periods. If it is found that hydrogen concentration in any compartment is far below a detonation criterion during an accident progression, it can be thought that the occurrence of a detonative explosion in a compartment is excluded. However, if it is not, it is necessary to evaluate the characteristics of flame acceleration in the containment.

The possibility of a flame transition from a deflagration to a detonation (DDT) can be evaluated from a calculated hydrogen distribution in a compartment by using sigma-lambda criteria. However, this method can provide a very conservative result because the geometric characteristics of a real compartment are not considered well. In order to evaluate the containment integrity from a threat of a hydrogen explosion, it is necessary to establish an integrated evaluation system, which includes a lumped-parameter and detail analysis methods. In this study, a method for the multi-dimensional analysis of hydrogen combustion is proposed to mechanistically evaluate the flame acceleration characteristics with a geometric effect. The geometry of the containment is modeled 3-dimensionally using a CAD tool. To resolve a propagating flame front, an adaptive mesh refinement method is coupled with a combustion analysis solver.

2. Methods and Results

2.1 Turbulent combustion model

There exist two groups of combustion models for a pre-mixed turbulent combustion. One is models based on flamelet, and the other group of models is based on the Arrhenius reaction rate. In the second group, there are two extreme models. One is the EBU (eddy breakup) [1] model in which the reaction is controlled by a mixing time scale. On the other end, there is a chemistry-controlled model, which is a PSR (perfectly stirred reactor) [2] model. Between the two models, EDC (eddy dissipation concept) [3] and PaSR (partially stirred reactor) [4] models exist. In order to simulate a flame propagating from slow to fast, an EDC or a PaSR model is more appropriate. A flamelet-based model requires a modification in order to be implemented under conditions of non-uniformly distributed hydrogen with steam. In this study, a PaSR model with a two-step hydrogen reaction is used.

$$3H_2 + O_2 \rightarrow 2H_2O + 2H \quad (1)$$
$$H + H + M \rightarrow H_2 + M \quad (2)$$

To validate the turbulence combustion model used in this study, the ENACCEF [5] experiment is simulated. ENACCEF is a test of hydrogen flame acceleration conducted by CNRS and IRSN.

The test facility is constructed in two parts, i.e., a tube part and a dome part. The tube part has many orifice-type baffles installed to accelerate a hydrogen flame. Fig. 1 shows the geometry of the ENACCEF facility modeled in this analysis and the flame propagating in the tube. In the experiment, the hydrogen flame is accelerated by the baffles in the tube. After passing the baffles, the flame is a little decelerated. The simulation gives very similar results as the experiment. In the dome region, the flame velocity from the simulation is very high compared to the experiment. Other simulation results show similar trends to the current one.

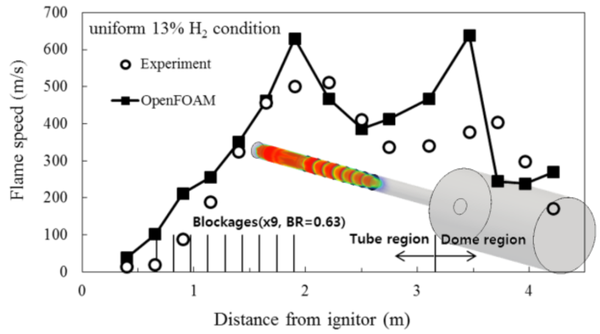

Fig. 1. Characteristics of flame propagation in ENACCEF: comparison of the flame speeds from the experiment and current numerical model.

2.2 Adaptive mesh refinement for flame front

To apply a turbulent combustion model in NPP containment, a high-performance computing technique is required because of the mesh size needed for a numerical capture of the flame. One of the methods is to use a massively parallel computer with a globally fine mesh. Another method is to use a local refinement with a flame front indicator. It only refines the mesh near the flame front. The combustion solver used in this study is already parallelized. In this study, the adaptive mesh refinement is coupled with the solver to run it on a desktop parallel computer. Fig. 2 shows refined meshes near a flame front propagating along with time.

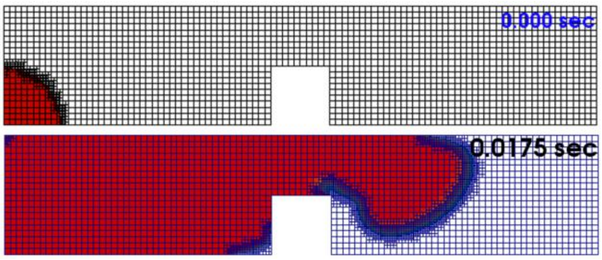

Fig. 2. Mesh refinement with a flame propagation

2.3 Containment Analysis

In this study, APR1400 was chosen for the application of the current hydrogen combustion model. A mesh generation for the containment requires 3-dimensional geometric information in a CAD format. It is obtained through a detailed review of the 2-dimensional drawings in the PSAR of Shin-Ulchin 1&2 [6]. An open-source CAD tool, freeCAD [7], is used for solid modeling of the internal structure of APR1400. The left side of Fig. 3 shows the modeled concrete structure inside the containment. The right figure shows the containment building in semi-transparent gray to visualize a relative arrangement of the internal structures. The modeled analysis domain of the containment is from the reactor cavity floor (elevation of 69 feet) to the apex of the containment dome (elevation of 329.5 feet). The length unit of the CAD data is converted from foot into meter.

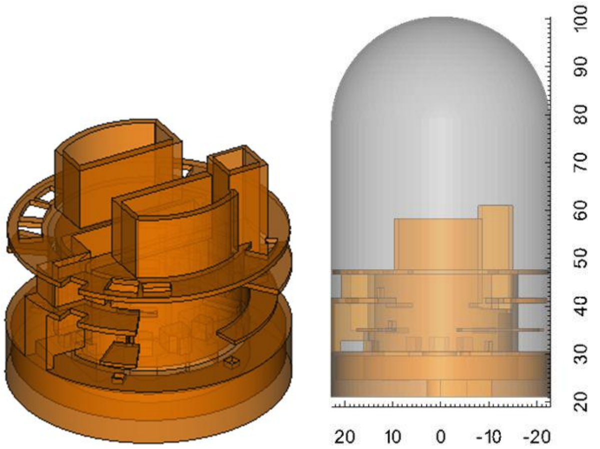

Fig. 3. 3-dimensional geometry model for APR1400 containment

To evaluate the characteristics of a hydrogen flame acceleration in a containment, thermal hydraulic conditions such as concentrations of gas species and temperature are required. It is planned as a future work to import the initial conditions of the solver from the results by GASFLOW [8] analyses because the current combustion solver does not include a steam condensation model. As mentioned above, hydrogen can be locally accumulated in compartments located in the flow path during the hydrogen release period. From a previous study [9], it was found that a highly concentrated hydrogen cloud may be developed in a steam generator compartment and dome region during a LOCA (loss of coolant accident) in APR1400. In this study, hydrogen flame behavior in the dome region is tested. It was assumed that hydrogen is accumulated in the dome region, as shown in Fig. 4.

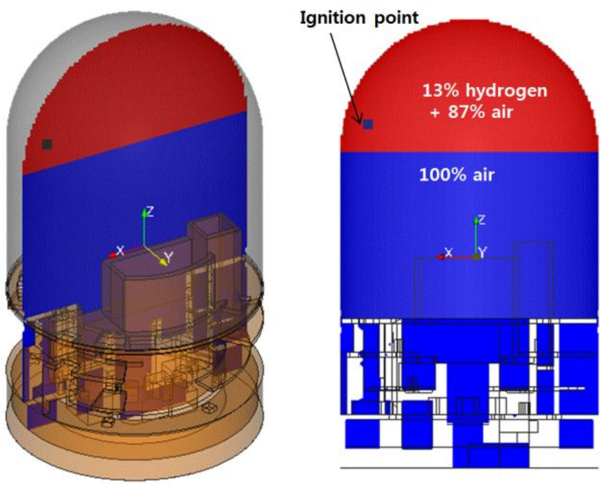

Fig. 4. Initial condition for a hydrogen combustion analysis.

An ignition source is assumed to exist near the wall in the dome region. Fig. 5 shows a snapshot of hydrogen flame propagation. The left figure depicts the refined region near a propagating flame in the mesh used for the analysis. The right figure shows the pressure field at a particular moment. It can be seen that the magnitude of the pressure exists in the range of AICC (adiabatic isochoric complete combustion) pressure.

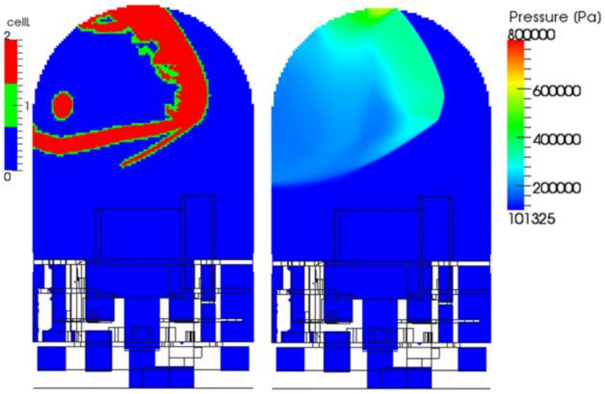

Fig. 5. Numerical results of 3-d hydrogen combustion, left: adapted mesh near a hydrogen flame, right: pressure distribution in the containment

3. Summary

It is important to evaluate the behavior of the hydrogen flames possibly occurring in a containment of a nuclear power plant during a severe accident. In this study, a numerical method for an analysis of 3-dimensional hydrogen combustion is developed and tested. In this method, an adaptive mesh refinement and de-refinement is used to capture a moving flame front with a reduced mesh size running on a desktop parallel computer.

To use the developed method for an evaluation of pressure loads on a containment wall from an accelerated hydrogen flame during a severe accident in an NPP, it is necessary to integrate it with a lumped-parameter severe accident code and a hydrogen distribution solver.

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