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H_2 Combustion Analysis in the Containment of APR1400 for a SBLOCA using a Multi-Dimensional H_2 Analysis System

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) established a multi-dimensional hydrogen analysis system for evaluating a hydrogen release, distribution and combustion in the containment of a nuclear power plant using MAAP, GASFLOW, and COM3D [1,2]. The COM3D analyze an overpressure buildup resulting from a propagation of hydrogen flame along the structure and wall in the containment using the hydrogen distribution result calculated by the GASFLOW. The MAAP evaluates a hydrogen source during a severe accident and transfer it to the GASFLOW. KAERI performed a hydrogen combustion analysis using the multi-dimensional hydrogen analysis system for a small break loss of coolant accident (SBLOCA) under the assumption of 100% metal-water reaction in the reactor vessel for evaluating overpressure buildup on the basis of the established COM3D analysis methodology.

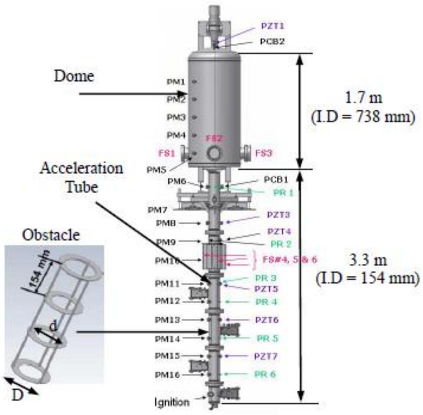
2. Methodology of the COM3D Analysis

2.1 Numerical Models in the COM3D [3]

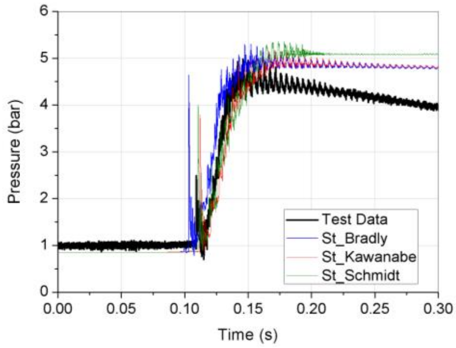
The COM3D is a fully explicit finite-differences code for solving the compressible Navier-Stokes equations in three-dimensional Cartesian space. The COM3D utilizes a set of transport equations for every gas species and for total energy, mass and momentum. For modeling of a turbulence flow during the hydrogen combustion, a Reynolds Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) model are implemented in the COM3D. The COM3D has a recently developed combustion model KYLCOM+ which uses the forest fire algorithm with the burning velocity model.

2.2 Proposed Analysis Methodology of the COM3D

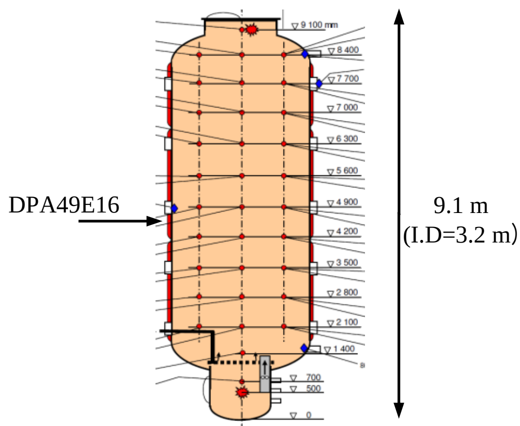
KAERI established the COM3D analysis methodology (Table 1) on the basis of the COM3D validation results (Fig, 1) against the test data of ENACCEF, THAI, and FZK Tube [4,5]. The proposed analysis methodology accurately predicted the peak overpressure with an error range of approximately ±25%. However, the COM3D analysis was not performed for the hydrogen combustion under the condition of the steam presence in a large-scale test facility.



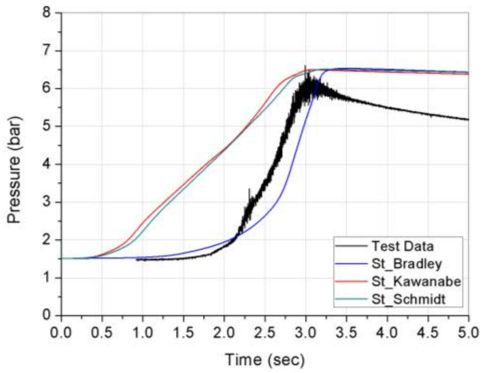
(a) ENACCEF Facility
(Test condition: H2 13%, Blockage Ratio 0.63)



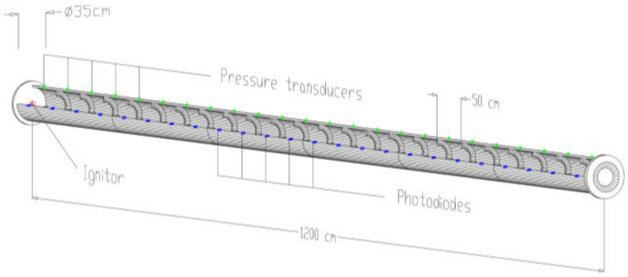
(b) Comparison of Pressure Behavior at PCB1 between Test Data and COM3D results (ENACCEF)



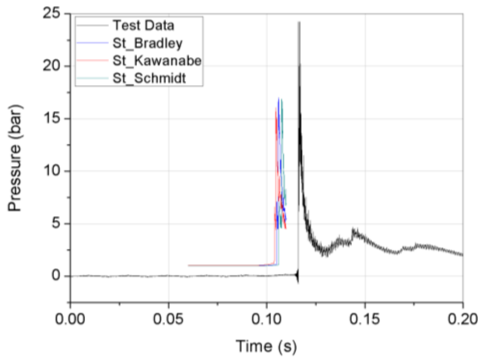
(c) THAI Facility (Test condition: H2 9.97%, No Obstacle)



(d) Comparison of Pressure Behavior at DPA49E16 between Test Data and COM3D (THAI)



(e) FZK Tube Facility
(Test condition: H2 15%, Blockage Ratio 0.3)



(f) Comparison of Pressure Behavior at 11.75 m from the ignition point between Test Data and COM3D (FZK Tube)

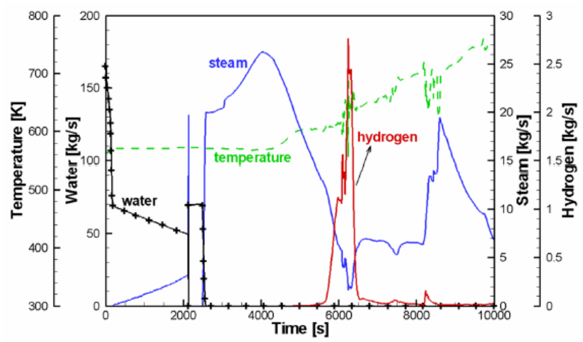
Fig. 1. COM3D Results for ENACCEF, THAI, and FZK Tube Tests

Table 1. COM3D Analysis Methodology

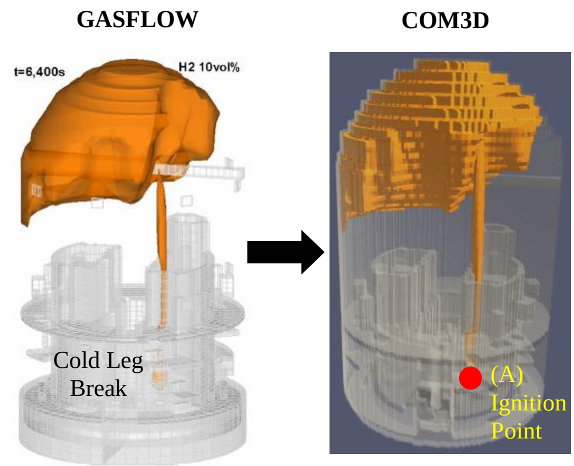
- Explicit solver : 2nd order TVD entropy based solver
- Combustion model : KYLCOM+
- Turbulent flame speed model : Bradley/Kawanabe/Schmidt
- Turbulent model : Standard k-ε
- Wall function : Low Re number and Launder Sharma
- Slip wall condition
- CFL number : < 0.9, RED number : < 0.4
- Mesh sensitivity results : Reference [5]

3. COM3D Analysis for a SBLOCA Accident

A COM3D analysis was performed to evaluate an overpressure buildup owing to a hydrogen flame acceleration in the APR1400 containment using the calculated hydrogen distribution by the GASFLOW for a SBLOCA accident under the assumption of a 100% metal-water reaction in the reactor vessel. The break position was assumed as a bottom part of the cold leg pipe. Fig. 2(a) shows the predicted hydrogen and steam generation rate by the MAAP. The grid model representing the APR1400 containment, as shown in Fig. 2(b), was also transferred from the GASFLOW to the COM3D by reducing the cell length to approximately 0.5 m. Therefore, a total of 1,453,025 hexahedral cells in the grid model were generated. The cell length in the grid model was determined to accurately resolve the pressure wave propagation generated from the combusted region [6] and model the important structures in the containment. The wall condition with a constant temperature of 298 K was applied to the inner surface of the grid model. The ignition points were assumed at the hydrogen release location around the cold leg in Fig. 2(b). An ignition process was modeled by the use of a hot spot region with a radius of 0.5 m where the hydrogen flame propagates with the laminar flame speed according to the hydrogen concentration. The analysis methodology (Table 1) chosen through the simulation of the ENACEEF and THAI tests was used for this calculation.



(a) Hydrogen and Steam Generation Rate (MAAP)



(b) Iso-surface of H_2 10% (GASFLOW and COM3D)

Fig. 2. MAAP and GASFLOW Results for the SBLOCA

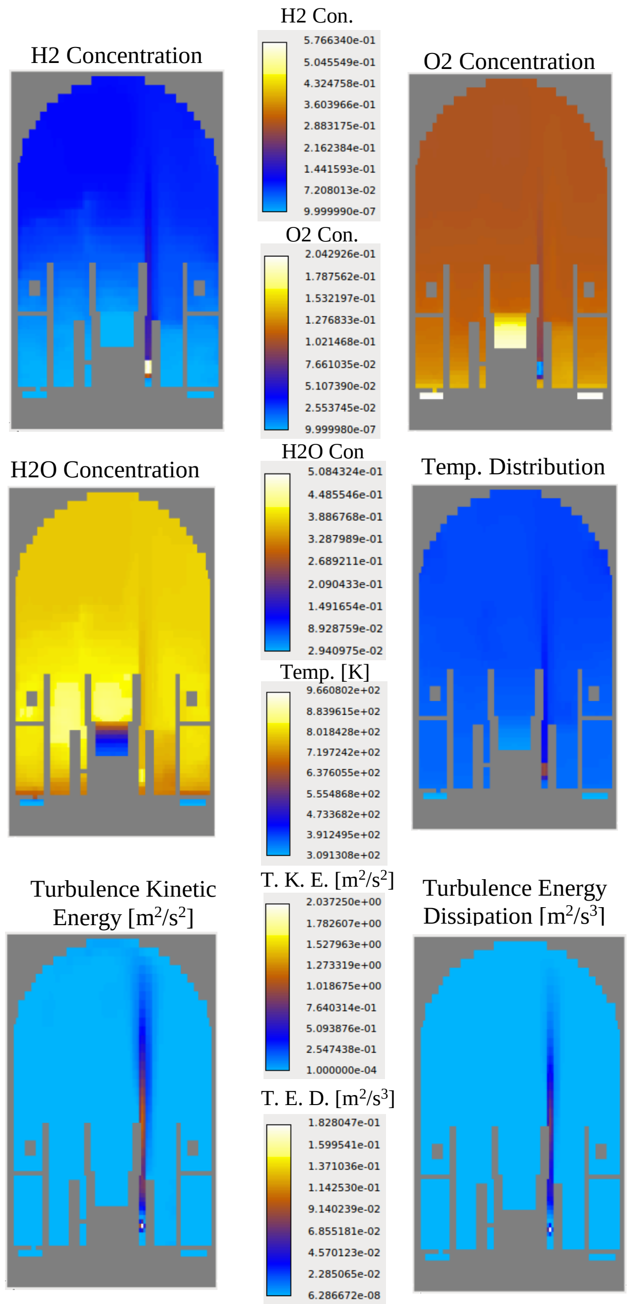
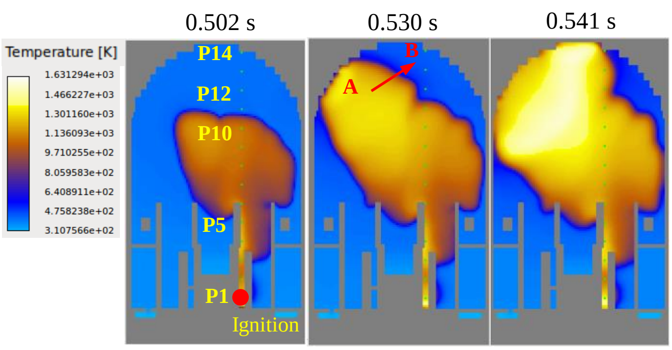
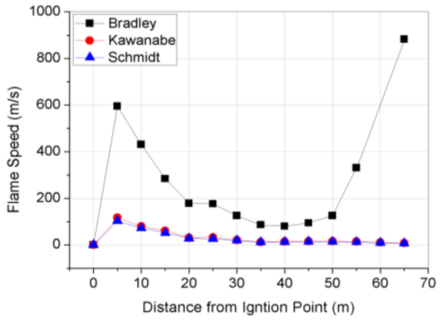


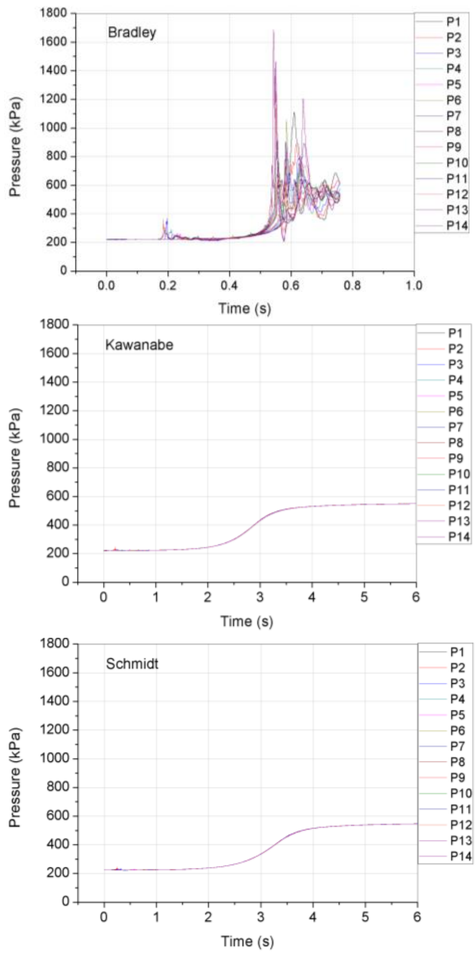
Fig. 3. Initial Conditions for the COM3D Calculation



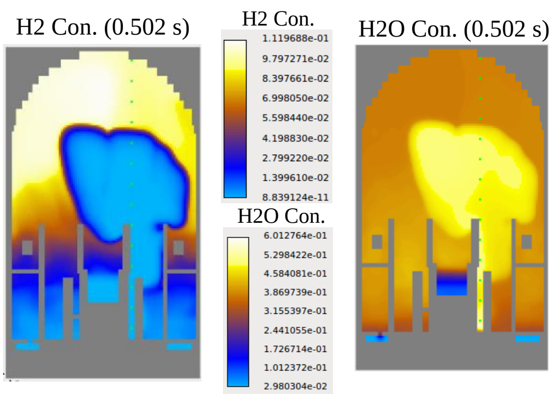
(a) Temperature Distribution (Bradley Model)



(b) Flame Speed from P1 to P14



(c) Pressure Behaviors from P1 to P14



(d) H2 and H2O Concentration (Bradley Model)

Fig. 4. COM3D results of the SBLOCA

The COM3D results based on the Bradley model show that the hydrogen flame is propagated to approximately 50 m (P1 to P10) along the vertical direction in about 0.5 s after the start of the ignition (Fig. 4(a)). The flame turns its direction toward the left upper wall after passing the points P5 to P10, and then the flame collides with the left upper wall (Fig. 4(a), A). The collided flame starts to propagate to the ceiling wall (Fig. 4(a), B). Thus, the calculated flame speeds is increased to approximately 900 m/s at around the ceiling wall (P12 to P14). The flame arrival time needed for calculating the flame speed was defined as the instant when the gas temperature increased to 1000 K at the locations of P1 to P14. The increased pressures owing to the flame acceleration are approximately 1700 kPa. This means that the containment integrity may be damaged by the overpressure buildup resulted from a strong deflagration phenomenon.

However, the COM3D results with the Kawanabe and Schmidt models show the slower flame speed and the low pressure increase shown in Fig. 4(b) and (c). The calculated flame speeds are approximately 10-20 m/s at around the ceiling wall and the pressure is increased up to approximately 500 kPa (Figs. 4(b) and (c)). This different results may be caused by that the predicted flame speeds at the region from the upper part of steam generator compartment to the left upper wall are greatly different when compared to the results by the Bradley model. The calculated flame speed by the Bradley model may be the overestimated results when considering the hydrogen concentration of about 11% and the steam concentrations of about 35% in the upper containment region (Fig. 4(d)). At this range of the hydrogen and steam concentrations, it may be difficult that the overpressure owing to the hydrogen flame acceleration is increased to approximately 1700 kPa from the initial pressure of approximately 200 kPa. Therefore, an additional COM3D validation should be performed using a large-scale test result with the hydrogen and steam contents for evaluating the flame acceleration phenomena according to the turbulent flame speed models.

4. Conclusions and Further Work

KAERI performed a hydrogen combustion analysis for a SBLOCA in the APR1400 using the multi-dimensional hydrogen analysis system under the assumption of 100% metal-water reaction in the reactor vessel. The COM3D results showed the different overpressure buildup according to the turbulent flame speed model between the Bradley model and the Kawanabe and Schmidt models. The predicted peak pressure by the Bradley model may damage on the APR1400 containment. To clarify the COM3D results difference between the turbulent flame speed models and increase the reliability of the COM3D calculation, an additional COM3D analysis should be performed for a large-scale test result with the hydrogen and steam concentrations which is similar to the concentrations distribution shown in the APR1400 containment through the SBLOCA analysis by the GASFLOW.

ACKNOWLEDGMENTS

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REFERENCES

[1] H. S. Kang, S.-B. Kim, and S.-W. Hong, Evaluation and Selection of a Multi-Dimensional Code for H_2 Combustion and Explosion Analysis in the Containment of a Nuclear Power Plant, Proceedings of KNS Spring Meeting, May 29-30, 2014, Jeju, Republic of Korea.

[2] H. S. Kang, J. Kim, S.-B. Kim, and S.-W. Hong, H_2 Combustion Analysis in the Containment of APR1400 for SBO Accident using a Multi-Dimensional H2 Analysis System, Proceedings of KNS Spring Meeting, May 12-13, 2016, Jeju, Republic of Korea.

[3] A. Kotchourko, A. Lelyakin, J. Yanez, G. Halmer, A. Svishchev, Z. Xu, and K. Ren, COM3D User / Tutorial Guide Version 4.9, KIT, 2015.

[4] A. Bentaib, et al., Final Results of the SARNET H2 Deflagration Benchmark Effect of Turbulence of Flame Acceleration, Proceedings of 5th ERMSAR-2012, Cologne, Germany, March 21-23, 2012.

[5] Kotchourko, A. et al.. ISP-49 on Hydrogen Combustion, Technical Report, NEA/CSNI/R(2011), OECD/NEA (2012).

[6] M. A. Movahed-Shariat-Panahi, Recommendation for maximum allowable mesh size for plant combustion analyses with CFD codes, Nuclear Engineering and Design, Vol.253, pp. 360-366, 2012.