Hydrogen Detonation Analysis for a PWR Containment Vessel*

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ABSTRACT

Flammable gasses and steam might have a potential to cause deflagration or detonation in severe accidents for a PWR plant. For providing information such as the influence of containment design and the effectiveness of accident management measures to the Level 2 PSA, multi-dimensional analysis methods for predicting hydrogen detonation behavior in containment vessel (CV) have been developed at NUPEC/INS. A hydrogen detonation code COMA was developed and validated as a method for predicting mechanical loads on the CV caused by the hydrogen detonation.

The High Temperature Combustion Test (HTCF) executed as a joint research of NUPEC and USNRC was simulated with the COMA code. Analysis results reproduced the experimental results: (1) propagation speed of reaction front and pressure behind reaction front, and (2) occurrences or non-occurrence of deflagration to detonation transition (DDT). The comparisons between experimental data and analytical results showed the applicability and validity of the COMA code to severe accident conditions.

Also, a hydrogen detonation phenomenon was analyzed by a two dimensional model for a pre-stressed concrete containment (PCCV). Pressure wave propagation, duration, and the maximum pressure caused by the hydrogen combustion were examined. When the detonation is promptly initiated after the hydrogen ignition, the maximum pressure appears inside the CV dome, not on the PCCV wall. The PCCV has a sufficient strength to withstand such pressure loads. But, if the distance from hydrogen ignition to a DDT point is long, the analytical results show that DDT was predicted at multiple point. The combustion wave reflects on the PCCV wall and interacts. Propagation behavior of the pressure wave after DDT becomes complex, and the maximum value and the distribution of the containment load vary depending on the locations of DDT.

I. INTRODUCTION

INS developed the mixing analysis code INSPAT/CV which can deal with spray droplet and multi-component

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gases, the deflagration analysis code DEFINE, and the detonation analysis code COMA [1] to examine containment hydrogen phenomena in case of PWR severe accident conditions. The three-dimensional effects by steam and hydrogen sources, hydrogen ignition points, and structural geometry in a containment can be simulated by these analysis codes. Moreover, the containment integrity for hydrogen detonation has been examined by a fluid-structure interaction analysis code AUTODYN [2].

First, regarding pressure propagation behavior of hydrogen detonation wave, the analytical capability of the COMA code was confirmed through the validation analysis of BNL hydrogen detonation tests. Next, two-dimensional detonation analyses were carried out for the PWR PCCV with COMA code.

II. THE ANALYSIS OF A BNL HYDROGEN DETONATION EXPERIMENT

The high temperature hydrogen combustion experiments were carried out using the High Temperature hydrogen Combustion Facility (HTCF) at BNL as a joint research [3] of NUPEC and U.S. NRC. The length of detonation tube used to conduct deflagration-to-detonation transition (DDT) experiments without vents is 21.3 meters long, and the spacing of orifice plates is equalized to the tube diameter (Figure 1). The orifice plates with blockage ratio of 0.43 to promote flame acceleration are 27.3 cm outer-diameter, which is equivalent to the inner-diameter of the tube, and 20.6 cm inner-diameter. A standard automobile diesel engine glow plug was used to ignite the test mixture at one end of the tube. The propagation analysis of detonation wave was performed with the COMA code.

A. Analytical Model and Conditions

In the analysis, it was assumed that the mixture gas of hydrogen and oxygen in the tube was completely uniform. A quarter analytical model of the experiment system was composed in consideration of geometrical symmetry. The analytical cell model of two-dimensional cylindrical coordinate system considered is shown in Figure 2. The radius direction is divided into 12. The analysis cell length of the propagation direction is set to about 10.5mm. The ignition position was used as the lowest cell at the left end of equipment. The initial conditions of the experiment selected for the analysis are atmospheric pressure, initial temperature 300K and 650K for hydrogen-air test, and initial temperature 400K and 500K for hydrogen-air-steam test.

B. Analysis Results

This analysis simulated the pressure history from hydrogen detonation initiation at the end of the experiment tube to the arrival of detonation wave at the another end where the reflection took place. The pressure propagation profile within the tube is shown in Figure 3. This figure shows a situation that the pressure of detonation wave rises by colliding with an orifice, and the detonation wave turns behind an orifice after passing the orifice. The propagation of detonation wave is obstructed by the existing orifice.

(i) Hydrogen-air Tests

Figure 4 shows the comparison of the calculated reaction wave propagation speed with the actual measurement in the case of the initial temperature 300K and 650K. this figure indicates that the COMA code can reproduce properly dependence of reaction front wave propagation speed on the initial hydrogen concentration. Moreover, the discontinuity of the propagation speed accompanied by in the combustion mode change is reproducible. In the case where detonation is predicted, the propagation speed is reproducible within about 10% accuracy. On the other hand, where the propagation wave concentrates on the choking location, the propagation speed tends to overestimate 10% or more.

(ii) Steam-hydrogen-air Tests

The comparison with the calculation value of the reaction wave propagation speed in the case of the initial temperature 400K and 500K and an actual measurement is shown in Figure 5. In initial temperature 500K, calculation value can reproduce the discontinuity of the propagation speed accompanied by the combustion mode change of chocking and detonation appeared in the tests of about 22% hydrogen concentration. In the steam-hydrogen-air tests where detonation is predicted, the propagation speed is also reproducible within about 10% accuracy. On the other hand, the propagation speed of chocking wave tends to overestimate, especially for the high hydrogen concentration case.

III. HYDROGEN DETONATION ANALYSIS FOR THE PCCV

A three-dimensional analysis model for a dry type PCCV was constructed for simulating a 4-loop PWR plant in Japan. A systematic analysis with the COMA code was conducted to study the detonation phenomenon in the PCCV. The purpose of the analysis was to compare the calculation result of a reaction wave front propagation action and the generated pressures between the COMA code and the AUTODYN-2D code.

A Analytical Conditions

(i) Containment Geometry and Meshing Scheme

The PCCV consists of an upper hemisphere dome and a lower cylinder. The containment height was calculated based on the containment free volume of 72,900m^3 and the inner radius of 20m. A quarter analytical model of the PCCV as shown in Figure 8 was applied in order to model the system considering geometrical symmetry on the cylinder coordinate system. Vertically the system was divided into 336 meshes, and radially 76 meshes in a two dimensional arrangement.

(ii) Initial Conditions

The initial hydrogen concentration distribution in PCCV was presupposed to be uniform. The range of the mean hydrogen concentration in the PCCV was assumed to be 5-20 vol% (dry). Initial temperature was set to be 400K considering the temperature rise by overheating steam for all analysis cases. Moreover, it was presupposed that initial pressure is also the same at atmospheric pressure (0.1013MPa). The ignition position was specified at the elevation of about 5/8 along PCCV center axis. An analytical parameter was only an initial gas composition. The gas composition was selected in the range of 5% to 20% of the hydrogen concentration and 0% to 25% of the steam concentration.

B. Analysis Results

The maximum pressures in the containment calculated with the COMA code is shown in Figure 7 relating to the combustion cell length.

(i) Cases with immediate DDD occurrence after ignition

DDT (deflagration and detonation transition) occurred quickly after ignition in Region A with combustion cell length smaller than 4 m. In this region, the maximum pressure in the dome top was limited to about 1/2 of the maximum pressure in the PCCV. In order that detonation wave form the single spherical wave centering around the ignition point, the maximum pressure occurs at the position which the reflective wave from a dome focuses. The propagation of detonation wave was predicted also with the AUTODYN-2D code [4], and the corresponding value is shown with symbol for the maximum pressure at the of dome top. The analysis result of detonation propagation is shown in Figure 8. The point that the maximum pressure in the PCCV was observed is about 15 m under the dome top.

(ii) Cases with DDT occurrence near the containment wall

In region B, once the propagation speed of reaction wave develops to the sonic speed, interfering pressure wave generated by collision with the PCCV wall results in DDT. In this case, as shown in Figure 9, detonation wave focuses near the top of dome, and the maximum pressure occurs. The propagation speed of pressure wave until it develops to DDT is mostly sonic speed, and the combustion mode is a choking. In this case, when about 20 mill-seconds from collision with PCCV was delayed, DDT is caused. In this case, 20 mill-seconds after the collision of pressure wave with the PCCV, DDT occurred. The maximum pressure has occurred around about 10 m under the dome top.

On the other hand, in Region C with the combustion cell length longer than 60 m, the final propagation speed of a reaction wave front is in the subsonic range which does not result in DDT. A limit of combustion cell length of 60 m is predicted for DDT occurrence in the PCCV geometry.

IV. CONCLUSIONS

The validation analysis for detonation experiments performed with HTCF of BNL as a joint research of NUPEC and USNRC has been carried out with the COMA code. Also, two-dimensional hydrogen detonation propagation have been analyzed for the PCCV of large dry containment types. The conclusions obtained from those analyses are summarized as follows.

A. BNL Test Analysis

Analysis results reproduced the experimental results that propagation speed on reaction front and pressure behind reaction front, and occurrences or non-occurrence of deflagration to detonation transition (DDT).

The comparisons between experimental data and analytical results showed the validity and applicability of the COMA code to severe accident conditions.

B. PCCV Analysis

(i) If the detonation is promptly initiated after the hydrogen ignition, the maximum pressure appears inside the CV dome, not on the PCCV wall. The PCCV has a sufficient strength to withstand such pressure loads.

(ii) if the distance from hydrogen ignition to a DDT point is long, the analytical results show that DDT was predicted at multiple point.

(iii) The combustion wave reflects on the PCCV wall and interacts. Propagation behavior of the pressure wave after DDT becomes complex, and the maximum value and the distribution of the containment load vary depending on the locations of DDT.

In order to obtain reliable analytical results of the containment load, more realistic simulation of the geometry is required. The field code is effective for simulating a real associated complex geometry, and concentration distribution of flammable gasses.

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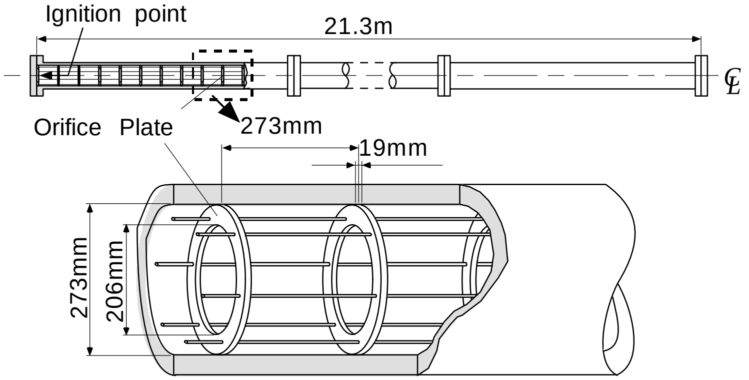

Figure 1 Geometry of HTCF Tests

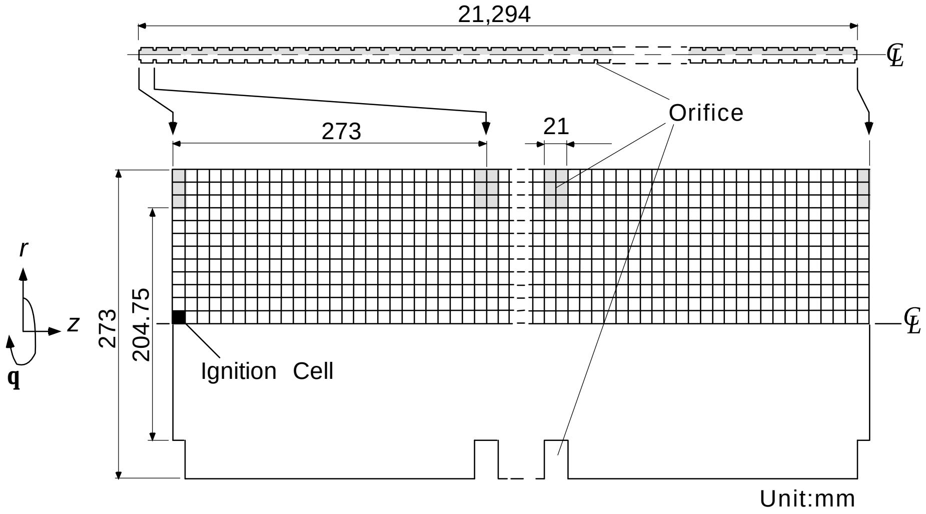

Figure 2 Mesh Arrangement for HTCF Tests Analysis

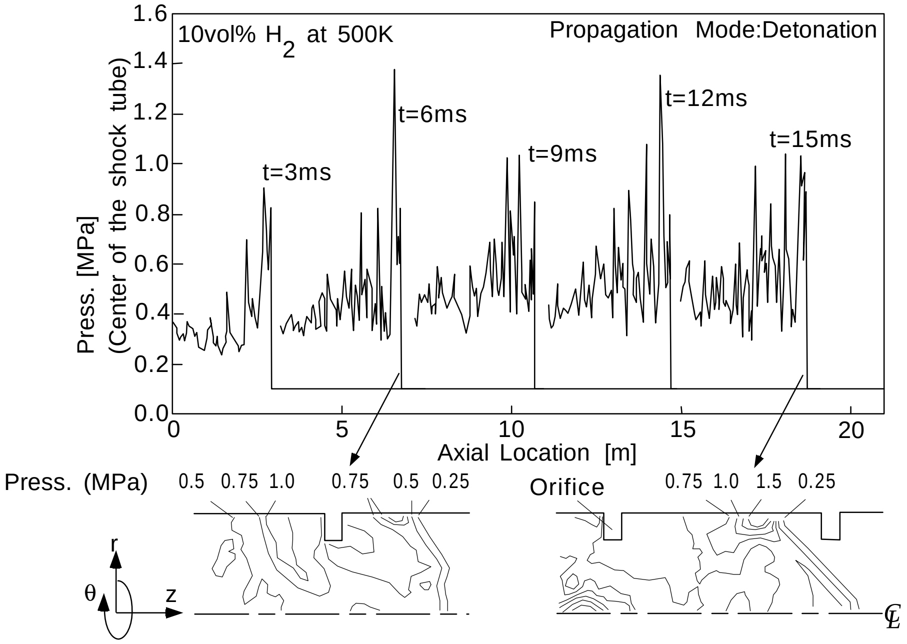

Figure 3 Typical Analysis Results(HTCF Tests Analysis)

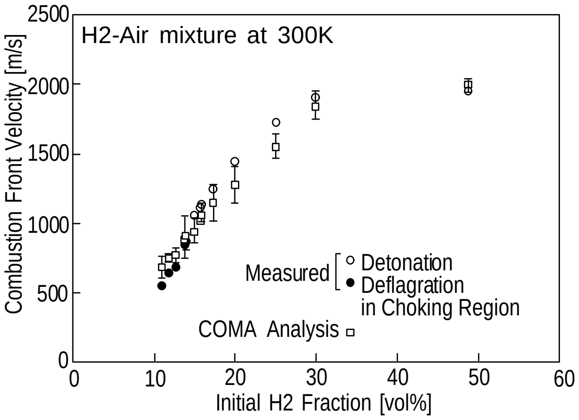

Figure 4 Combustion Front Velocity Comparisons
(H2-Air mixture/H2 Frac. Dependency)

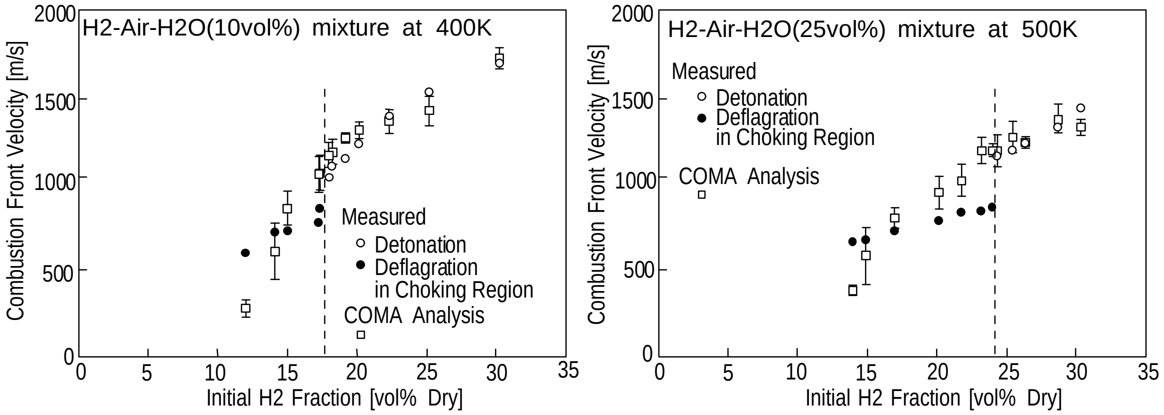

Figure 5 Combustion Front Velocity Comparisons
(H2-Air-H2O mixture/H2 Frac. Dependency)

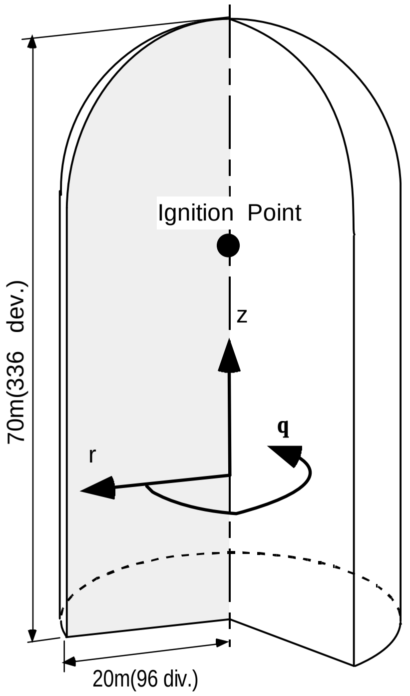

Figure 6 Analytical Geometry and Modeling

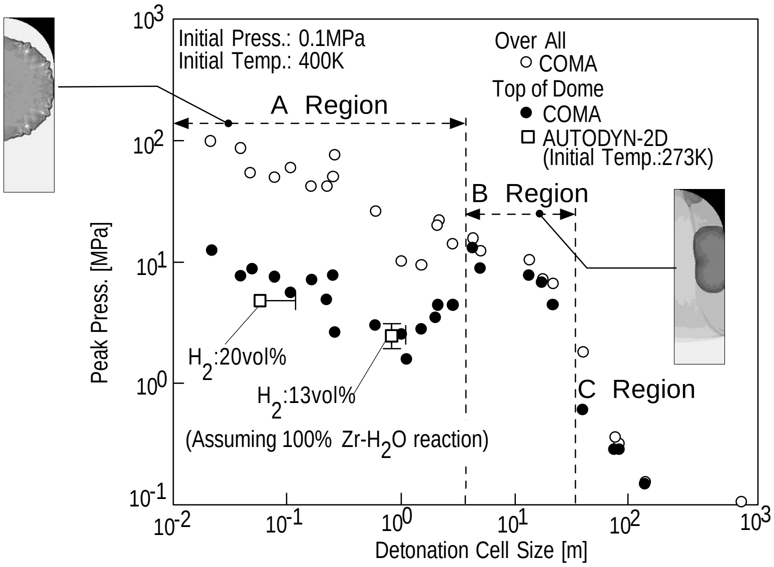

Figure 7 Peak Pressure Analytical Results

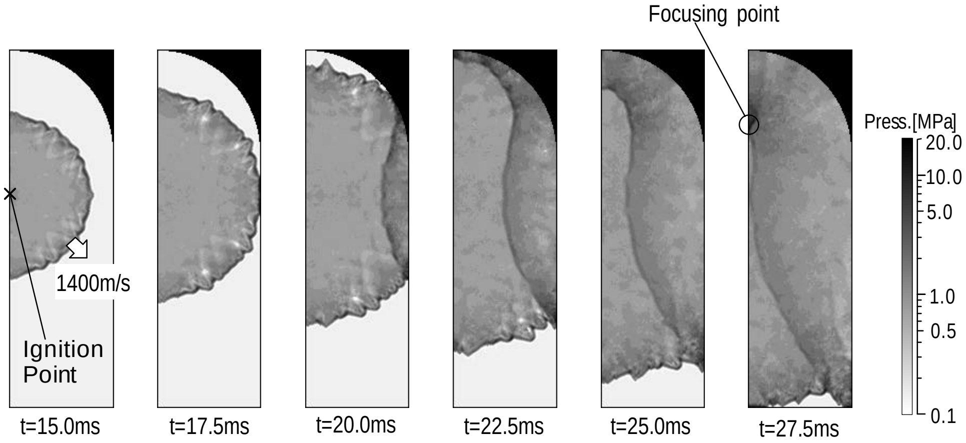

Figure 8 Typical Result of PCCV Detonation Analysis

H_2(19vol%)-Air-$H_2$0(5vol%) mixture at 400K

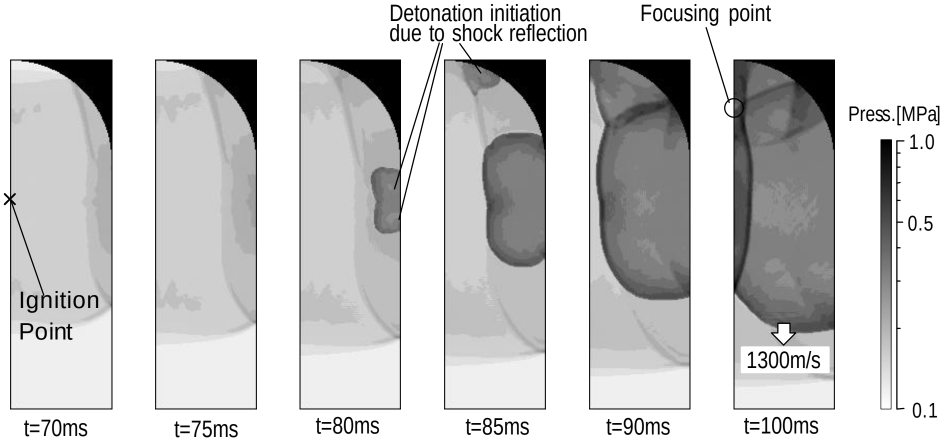

Figure 9 Typical Result of PCCV Detonation Analysis

H_2(7vol%)-Air mixture at 400K