Analysis of Hydrogen Behavior in a PWR Containment Vessel under Spray Operations

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Abstract

When a containment vessel (CV) of PWR is overpressured by steam and hydrogen generated in the core and transported to the CV during severe accidents, the vessel is immediately depressurized by a CV spray system through steam condensation. Then relative concentration of hydrogen becomes higher, and a chance of hydrogen burn or detonation with a concern of damage to the vessel with extremities may occur. Another concern is locally high concentration of hydrogen driven by density difference. Therefore, it is one of safety concerns to examine the effects of CV spray and such associated synergetic events, as steam condensation, depressurization and hydrogen stratification or mixing driven by possible circulation flow with the CV.

The present paper deals with three-dimensional analysis of thermal hydrodynamics in the vessel under spray operations performed by INSPAT/CV, which can analyze the performance of droplets and multi-components gases and has been developed at INS/NUPEC.

In the analysis, the hydrogen behavior was calculated for various conditions of spray operation under conservative assumptions of localized hydrogen accumulation at the top of the vessel. As regarding spray operations, droplets flow rates and spray patterns from four spray rings at different vertical locations were varied as parameters. The analysis results showed that spray droplets induced a circulation flow in the vessel with a downward flow near the wall sides induced by falling droplets, and a upward flow around the center of vessel. This circulation flow rapidly diffused and mixed hydrogen accumulated locally at the top, and homogenized hydrogen concentration in the vessel. Regarding a low flow rate operation of CV spray, a possible operation mode for accident management (AM) was simulated. It was found that even a 1/10 of normal flow rate only from the lowest spray ring was still effective for hydrogen diffusion and mixing.

1. Introduction

During severe accident of nuclear power plant, flammable gases are generated by interaction between fuel cladding and coolant in the core or during core-concrete interaction in the reactor cavity. These flammable gases are transported to the CV with steam through release pathways from the primary coolant system and the reactor cavity. The vessel would be overpressured by the accumulation of gases and possibly result in CV failure. However, the CV pressure is rapidly decreased due to steam condensation by an operation of CV spray system. After the operation of the CV spray, concentration of hydrogen becomes relatively higher with steam condensation. The energetic reaction between hydrogen with high concentration and oxygen in the CV may occur with a concern of damage to the vessel. Another concern is a localization of hydrogen due to diffusion that leads to high concentration of hydrogen. The hydrogen combustion is dependent on its concentration and results in energetic burning as deflagration or detonation under high concentration (e.g. 14vol% for detonation). In reality, however, hydrogen combustion is considered to be relatively slow because hydrogen concentration doesn't become higher with diffusion and mixing by possible circulation flow induced by spray droplets.

A CV spray operation with the alternative injection system is examined as one of the measure of AM. The system achieves injection of water in the CV with the fire pumps or substitutive pumps in case of failing CV spray pump operation. The system can not spray from higher location nozzle and has low flow rate because these pumps have lower head than the CV spray pump. Hence, it is necessary to confirm the effect of AM measure on hydrogen diffusion and mixing with analysis under low flow rate with the alternative injection system.

Therefore, it is one of safety concerns to examine the effects of CV spray on hydrogen behavior and such associated synergetic events, as steam condensation, depressurization and hydrogen stratification or mixing due to possible circulation flow with the CV.

Improvement of analysis code for thermal hydrodynamics and hydrogen combustion in the CV

At INS/NUPEC, INSPAT/CV for thermal hydrodynamics, DEFINE for deflagration, COMA for detonation, and AUTODYN for boundary response by shock wave due to detonation have been developed and improved as a series of computer codes for analyzing phenomena in the CV during severe accident. Figure 1 shows the relation of these codes. Two kind of analysis codes, DEFINE and COMA, are improved for the detailed analysis of hydrogen combustion. These codes use different model because combustion phenomena of deflagration with subsonic flame propagation and detonation with supersonic flame propagation are essentially different.

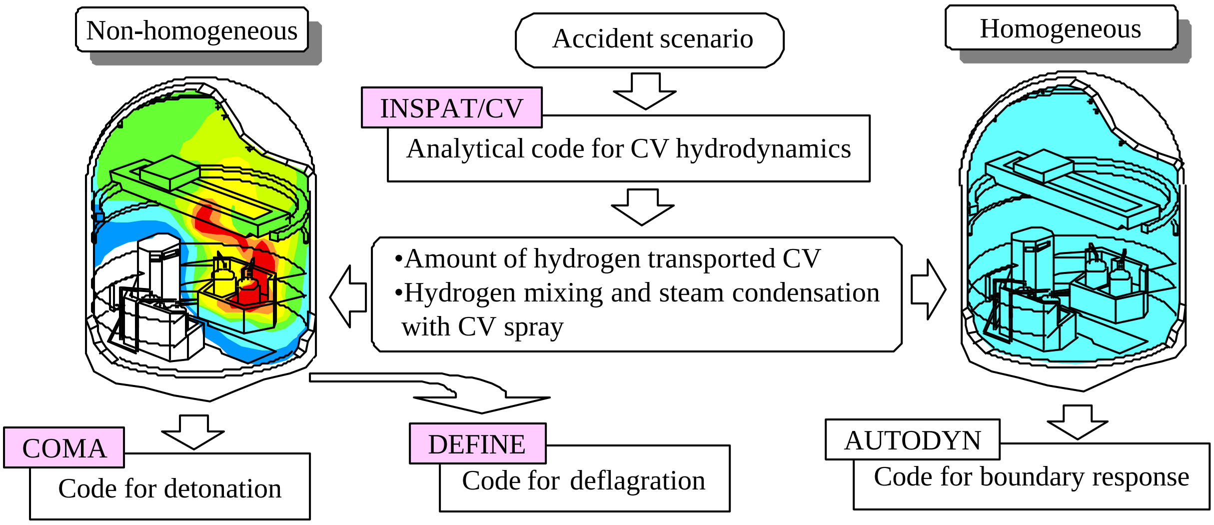


Fig.1 Relation of analytical codes for hydrogen combustion

Transportation of hydrogen in the CV becomes very complex with existence of large constructions as steam generator rooms, pressurizer compartment, and crane in PWR containment vessel. Since the circulation flow and flame propagation are strongly dependent on the configuration of structures in the CV, development of three-dimensional codes should be needed.

The outlines of INSPAT/CV, DEFINE and COMA are given as follows;

INSPAT/CV

The INSPAT/CV code calculates thermal hydrodynamics with BFC (Boundary Fitted Coordinate) grids for non-compressible fluid. Droplets model and steam condensation model were incorporated in the code to simulate prevention of overpressure by condensing steam with spray during severe accident. Droplets model is incorporated to analyze interaction between droplets and atmosphere, and the INSPAT/CV code also simulates induced circulation flow in the CV. In addition, the diffusion and mixing of specific gas can be calculated with multiple-component gas transportation model.

DEFINE

The DEFINE code calculates deflagration with subsonic flame propagation for compressible fluid. Basic equations are consisted of mass, momentum, and energy conservative equations, characteristic equation for ideal gas and mass conservative equations for every chemical component. For chemical reaction model, Overall reaction model or elementary reaction model is implemented based on Arrhenius's equation, alternatively. In addition, k-ε model as turbulent flow model and eddy-dissipation model of Magnussen as turbulent combustion model are used in the code.

COMA

The COMA code calculates detonation with supersonic flame propagation and propagation of shock wave in multi-component gas or steam-water two-phase flow with thermal non-equilibrium. Thermal conductivity in the gas and diffusion of gas component are not treated because they are long-term phenomena comparing with a few hundred milliseconds for shock wave to propagate over the vessel. It assumes that component is transported by only convection. Chemical reaction starts by high temperature induced by adiabatic compression when shock wave arrives. Data table for the chemical reaction model was prepared with the CHEMKIN code.

2. Sensitivity analysis for various conditions of spray operations

2.1 Analytical condition

Analysis is carried out for the CV of 1100MWe four-loop PWR (shown in figure 2). BFC grids for calculation are shown in figure 3. Pressurizer compartment, steam generator, chimney of steam generator and crane set up as obstacles in the grids to be taken the effects of these components on circulation flow into account. The number of total mesh was 22,000.

Droplets were sprayed from 350 nozzles placed spray rings. For simplification of analysis, nozzles separated 82 groups with four or five nozzles into one group.

The present paper deals with sensitivity analysis including low flow rate of AM to evaluate the effects of CV spray on diffusion and mixing of hydrogen by the INSPAT/CV code. In the analysis, the hydrogen behavior was calculated for various conditions of spray operation under conservative assumptions of localized hydrogen accumulation at the top of the vessel. It neglects steam condensation and calculates only diffusion and mixing of hydrogen by circulation flow under spray operations.

2.2 Initial condition

In all cases, calculation was started under the initial condition of hydrogen stratification at the top of vessel. That is, molar fraction of hydrogen at the top of vessel was 1.0. The average molar fraction of hydrogen in the vessel was 0.21. Initial pressure and temperature were 0.3MPa and 400K respectively all over the vessel, from the information of MELCOR results. Atmosphere did not have any flow in the vessel at first.

2.3 Analytical parameter

Spray flow rate and the pattern of operated spray rings were selected as analytical parameters because they affected possible circulation flow in the CV. Six cases were selected in Table 1.

In case 6, analysis was carried out for spray with substitutive pump in AM. It is much different from other cases on that only lowest spray ring was available because substitutive pump got lower head compared with CV spray pump. Spray flow rate was 1/10 of normal CV spray flow rate.

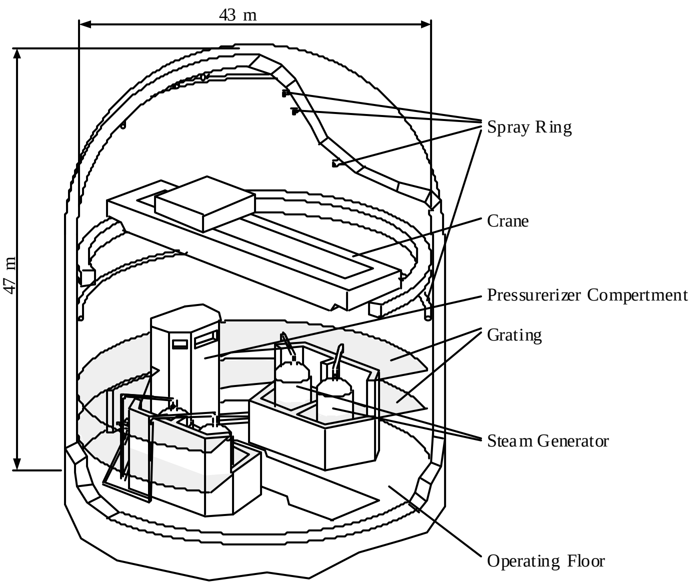


Fig.2 View of four-loop PWR

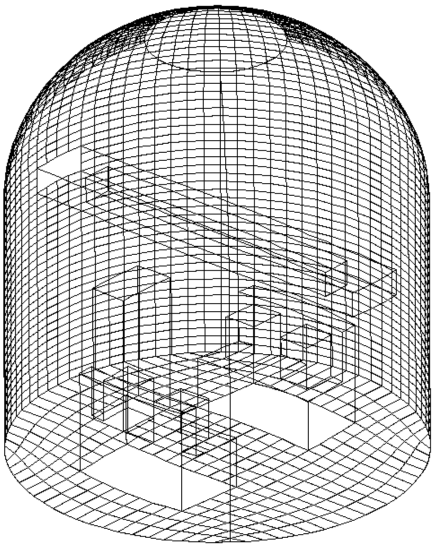
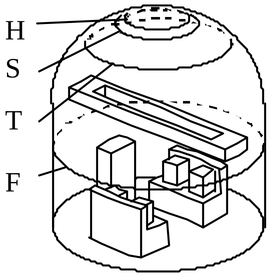


Fig.3 Calculation grids

Table.1 Analytical parameter

<table>
<tr><th>No.</th><th>Flow rate of spray</th><th>Available spray rings</th><td rowspan="7">

Location of spray rings</td></tr>
<tr><td>1</td><td>600</td><td>All</td></tr>
<tr><td>2</td><td>120</td><td>All</td></tr>
<tr><td>3</td><td>1200</td><td>All</td></tr>
<tr><td>4</td><td>600</td><td>H,T</td></tr>
<tr><td>5</td><td>600</td><td>S,F</td></tr>
<tr><td>6</td><td>240</td><td>F</td></tr>
</table>

H : Highest ring
S : Second ring
T : Third ring
F : Fourth ring

3. Results and discussion

3.1 Mixing phenomena with circulation flow induced by CV spray

The droplet distribution and the velocity distribution of induced circulation flow show in figure 4 and figure 5 respectively, as typical results. The downward flow along the CV wall was come out due to drag force of droplets falling along the wall. After the downward flow reached onto the floor, the fluid flow changed the direction and went to the center of the vessel. Then, the gas gathered at the center of the vessel became upward flow and moved to the top of the vessel. This upward flow moved to around spray nozzles and became downward flow again due to the interaction with droplets. The stratified hydrogen at the top of vessel was well mixed with the circulation flow in the vessel.

The standard deviation for hydrogen-mixing rate was calculated from hydrogen molar fraction of all mesh. The lower standard deviation means more homogeneous distribution of hydrogen. Figure 6 shows the result of the case 1. Hydrogen was dispersed all over the vessel at about 15 seconds after spray operation started. Since the standard deviation after 60 seconds was less than 1%, hydrogen distribution became homogeneous all over the vessel around one minute after spray initiation.

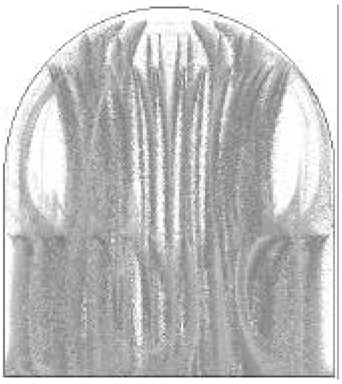


Fig.4 Droplets distribution (Case 1)

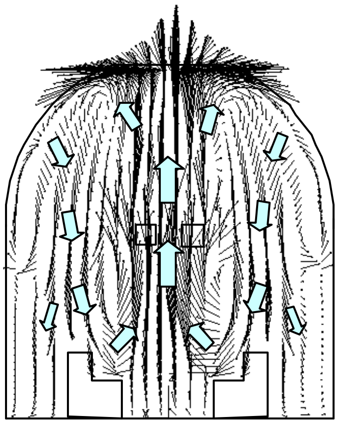


Fig.5 Velocity distribution (Case 1)

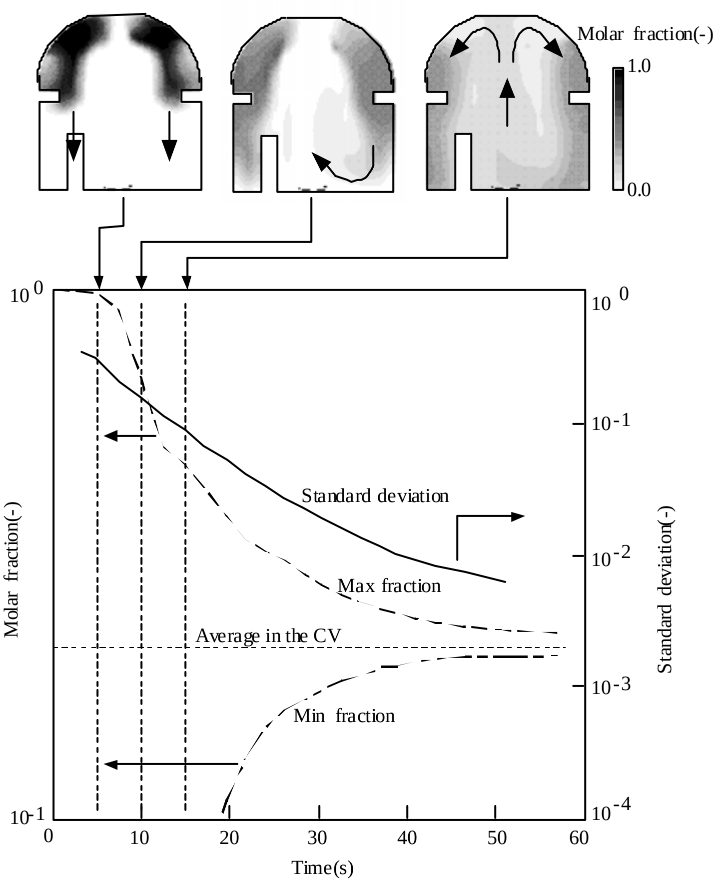


Fig.6 Hydrogen concentration profile (Case 1)

3.2 Effect of spray flow rate on mixing

Sensitivity analysis was carried out to confirm the effect of spray flow rate in the conditions of cases 1 to 3. Results are shown in figure 7. Time for mixing of stratified hydrogen became faster with increase of spray flow rate. However, it appeared no significant difference between single pump and 1/2 pump flow rate. The results indicate that mixing time might be saturated with by single pump flow rate. Downward flow increases with more spray flow rate, and then diffusion and mixing are hastened with increasing circulation flow rate. However, more droplets reach to the center hinder upward flow in case of increasing spray flow. This effect is saturated circulation flow rate and hydrogen mixing time.

The results also show that hydrogen was mixed sufficiently in two minutes even with 1/20 of normal spray flow rate. It is pointed out that spray operation even with low flow rate is very effective for avoiding hydrogen localization in the vessel.

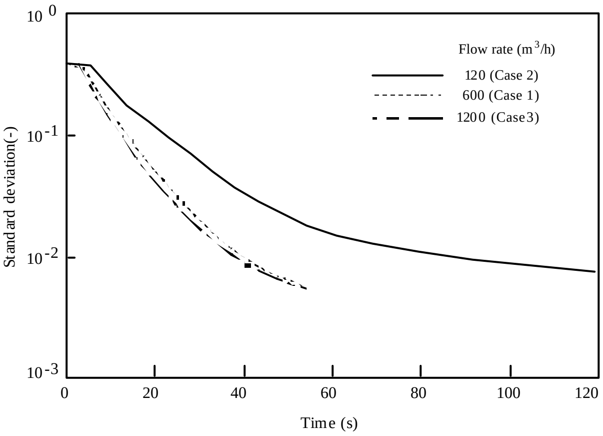


Fig.7 Hydrogen concentration

3.3 Effect of pattern of operated spray rings

The pattern of circulation flow induced in the vessel may change with the pattern of operated spray rings. To confirm the effects of spray location on diffusion and mixing of hydrogen, analysis was carried out under the assumption of spray from specified spray rings.

First analysis was carried out under spray operation with the highest location and the third spray rings. Figures 8 and 9 show the calculated results of droplet distribution and velocity distribution of induced circulation flow. Upward flow was formed at the center of the vessel as well as spray from all rings. Another upward flow was formed along the vessel wall without obstructive droplets from fourth rings and resulted in decrease of flow rate at the center. These two kinds of circulation flow promoted diffusion and mixing of hydrogen effectively all over the vessel.

Second analysis was carried out under spray operation with the second and the fourth spray rings. Figures 10 and 11 show the calculated results. In this case, downward flow was formed at the center of vessel with droplets from second spray ring. The circulation flow was induced at the wall side region between second and fourth rings. The stagnation points came out around chimneys of steam generators where flow velocity became small.

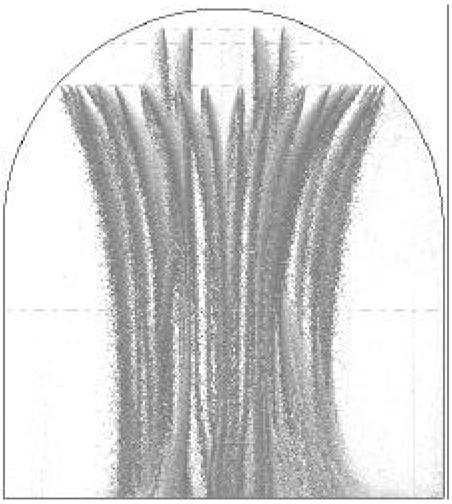


Fig.8 Droplets distribution (Case 4)

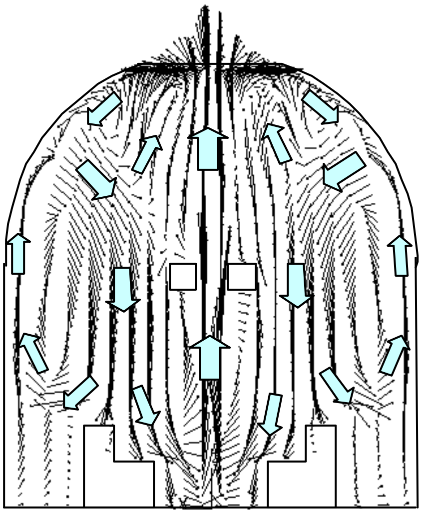


Fig.9 Velocity distribution (Case 4)

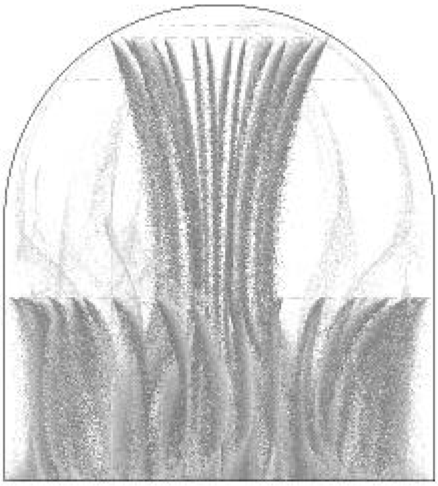


Fig.10 Droplets distribution (Case 5)

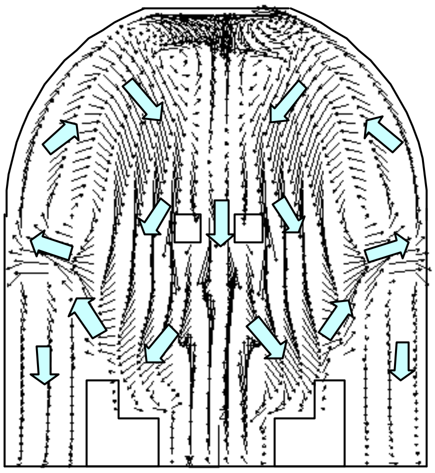


Fig.11 Velocity distribution (Case 5)

Figure 12 shows the effect of spray rings pattern on hydrogen mixing. Spray operation from the highest location and the third spray rings became effective for homogenization of hydrogen all over the vessel. In this case, circulation flows induced at both sides of the center and the wall became effective for diffusion and mixing of hydrogen in all over the vessel. Spray operation from the second and the fourth rings took longest time for hydrogen mixing in three cases. In this case, stagnation came out at around the chimneys of steam generators because circulation flow was formed at only higher region from fourth ring level.

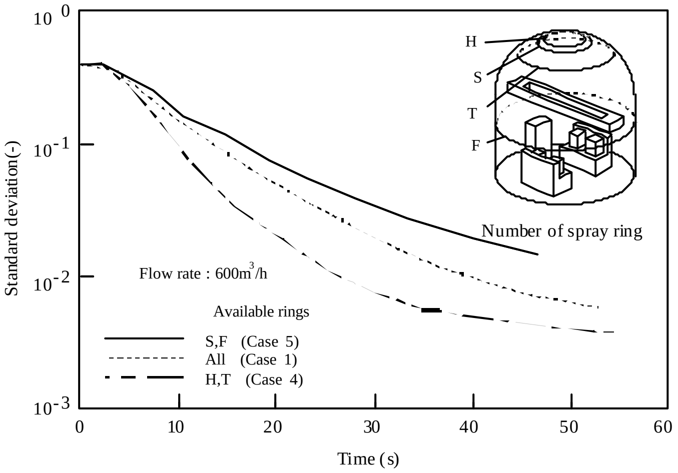


Fig.12 Hydrogen concentration

The calculated results show that the pattern of spray from highest and third rings is very effective for diffusion and mixing of hydrogen. This pattern easily occurs wide circulation flow all over the vessel and disappears stagnation points because there are few droplets hindering upward flow around the chimneys with spray just above them.

3.4 Spray with substitute injection system

With consideration of substitute pump's low head, droplets were sprayed from only the lowest ring in the case 6. Figures 13 and 14 show droplet distribution and velocity distribution of induced circulation flow. Downward flow was induced besides the wall by drag force due to droplets. The direction of the flow was changed upward at the center of the vessel. Clear circulation flow was formed at only lower region from the fourth ring, but a part of upward flow moved to the top of vessel and contributed to stratified hydrogen mixing. Figure 15 shows the effect of substitute injection system on hydrogen mixing. The results show that hydrogen is mixed sufficiently in a minute with less than 1% of standard deviation and spray even with substitute pump is effective for mixing of hydrogen stratified at the top of vessel.

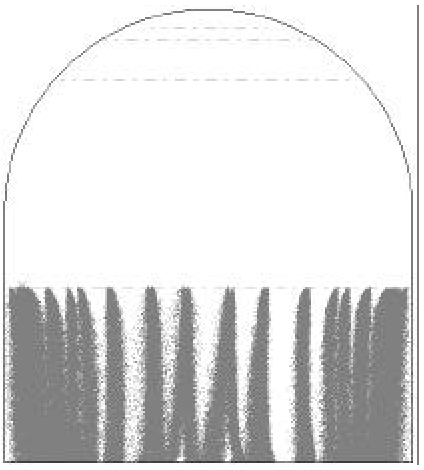


Fig.13 Droplets distribution (Case 6)

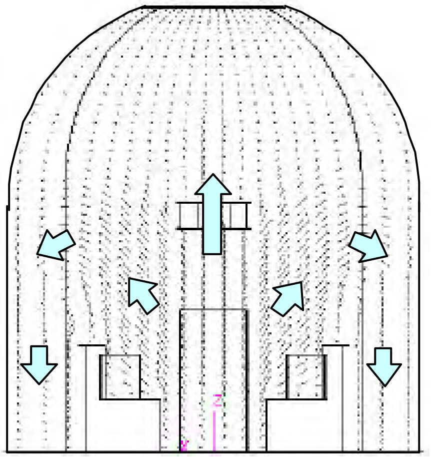


Fig.14 Velocity distribution (Case 6)

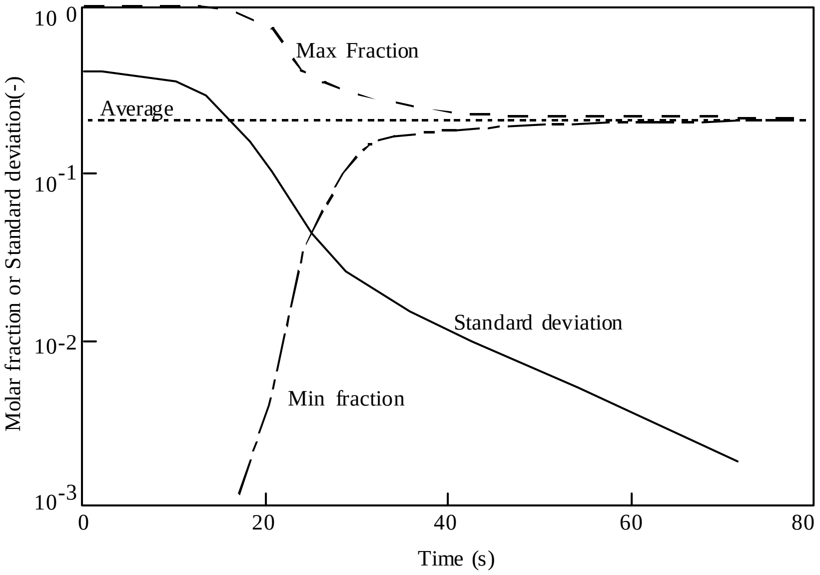


Fig.15 Hydrogen concentration profile (Case 6)

4. Summary and Conclusion

A series of analysis codes are improved and developed for analyzing thermal hydrodynamics in the CV including hydrogen combustion during severe accident. In the present study, sensitivity analysis for mixing phenomena of hydrogen stratified at the top of vessel with spray operation was carried out with INSPAT/CV, thermal hydrodynamics analytical code in the CV.

The results of the present study showed that (a) 1/20 of normal flow rate from all spray rings mixes and homogenizes hydrogen stratified at the top of vessel in two minutes, (b) low flow rate (1/10 of normal flow rate) from only the lowest ring is effective for hydrogen mixing. Later condition corresponds to the spray operation with substitute injection system for AM. The results support the effect of AM measure that can control hydrogen stratification during sever accident.