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Hydrogen risk analysis of CANDU Type NPP using multi-dimensional code GASFLOW-MPI

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1. Introduction

In case of severe accidents of nuclear power plant, hydrogen may be produced due to the reaction between the cladding material, concrete and several metals and the steam in reactor vessel. For the BWR plant, hydrogen and other gas species including steam may be discharged into the containment building through possible break locations; reactor outlet header(PHTS), DCT(degasser condenser tank), calandria tank rupture valve and reactor vault's rupture disk. If a lot of steam is released and local conditions of combustion are reached to some criteria and an energetic hydrogen results in the containment integrity threat. Currently, domestic nuclear power plants are safely operating with sufficient margin for such hypothetical accidents. In other to mitigate against the possible (unlikely) hydrogen threats, the passive autocatalytic recombiners (PARs) are installed inside the containment building. To evaluate the possibility of hydrogen combustion and effect of hydrogen removal of PAR, several codes had been used such as MAAP-ISAAC[1], MELCOR[2], etc. These are so called the lumped parameter (LP) codes. These codes had been applied under the typical background that the containment atmosphere will mixed well during the accident. On the contrary, GASFLOW-MPI is a CFD-like code specialized in hydrogen hazard analysis of the containment building and is maintained and developed as at KIT[3, 4, 5].

The purpose of this research is to evaluate the multi-dimensional effect of hydrogen behavior and to evaluate the validity of the hydrogen control system(PAR) in the event of a severe accident inside the containment building of CANDU type.

2. Modeling of CANDU Type Containment Building

For analysis using GASFLOW-MPI, a geometric model of the containment building is required first. From this model, the computational domain (fluid zone) is defined and the grid modeling required for numerical analysis is performed. After the set-up of grid model, the initial conditions, boundary conditions (flow and wall) and component elements (PAR, SPRAY, CFVS, etc.) required for analysis are arranged. These sequential procedures are the same as typical CFD analyses except that the final input has a text-based form. While preparing the input model, the several programs are used additionally also. The mass/energy data release into containment used in this research is from the result of the MAAP-ISAAC preceding analysis that has been performed separately.

2.1 Geometric Mode of Containment Building

In the first stage, the geometric model of the containment building of CANDU type NPP is modeled using the Solid-works CAD program. The outer wall of containment building and the internal concrete structure including the major components are modeled. These structures are then recognized as a solid zone that is separated from the fluid zone and the surface of these solid zones can be adopted as a boundary to transfer the heat with the fluid zone. GASFLOW-MPI code has a sink heat structure, which allows user to model structures with tiny and complex shapes so that these are difficult to be drawn in geometry. This sink model was used in this analysis also. Figure 1 shows a geometric model of containment building prepared in this analysis.

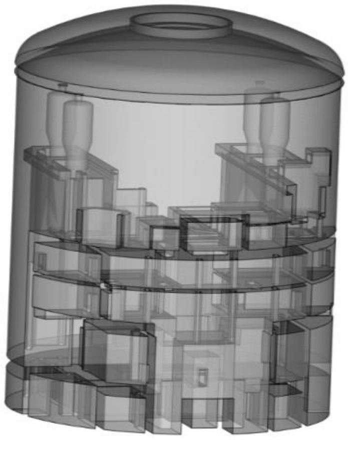


Fig. 1. Geometric shape of CANDU type NPP containment building

2.2 Grid Model of Computational Domain

After the geometry is complete, the gfmesh tool is used to create a grid of computational domain. The gfmesh tool divides the computational domain by the number designated by user with cartesian coordinate. The gfmesh tool provides the coordinate information including the separator that recognizes the fluid and solid zone. Figure 2 shows a grid model created using the gfmesh tool. In this research, 80 x 80 x 90 meshes along x, y and z directions are respectively applied for the containment building and the environment zone and the total number of grids used in the analysis is 576,000.

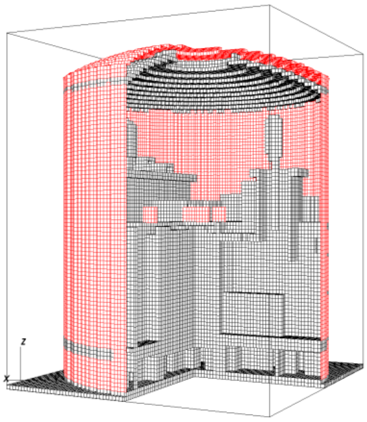


Fig. 2. Grid model of CANDU type NPP containment building

2.3 Input Model and Equipment

The GASFLOW-MPI code has three kinds of thermal structure and uses a one-dimensional heat conduction equation for all kinds of structures. Wall and Slab type structures use boundary conditions designated by the user on surfaces of solid zone and geomodel. Sink, on the other hand, is used to distribute virtual heat structures to user-specified cell groups, not to the surface of solid zone or geomodel. In this research, many actual heat structures that cannot be described in geometric model are replaced with Sink structures which were selected from all lists of passive heat sink.

The dowsing spray system of CANDU type NPP is designed to operate when the containment pressure reaches 1.14 bar. In this research, the location where the spray nozzle is present (El = 135 m) was evenly placed over a total of 72 grids. All 72 spray nozzles flow at the same rate but it changes over time at a rate obtained from the MAAP-ISAAC analysis.

A CFVS (Containment Filtered Venting System) is installed in CANDU type NPP. To reflect this in the analysis, the flow boundary on the wall where the CFVS discharge piping is located is assigned. The CFVS discharge flow rate is from the results obtained in the MAAP-ISAAC analysis also.

The total number of 27 PARs(6 units for design basis accidents and 21 units for severe accidents) as the hydrogen control equipment is installed in CANDU type NPP containment building. These are distributed over the containment upper free volume space, steam generator, moderator and F/A compartments.

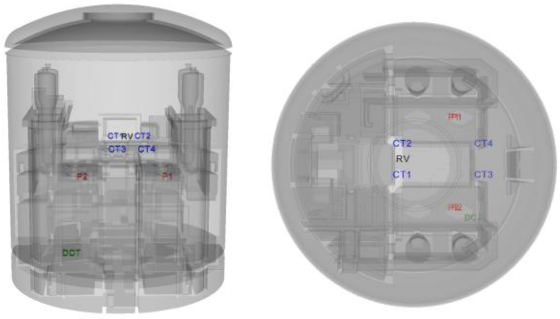
2.4 Accident Scenarios and Mass/Energy Release

In this research, a total of four accident scenarios were analyzed and the list is as follows;

- Case1 : Loss of Raw Service Water due to a flooding event
- Case2 : Loss of Class IV Power with CFVS Operation
- Case3 : Loss of Class IV Power without CFVS Operation
- Case4 : Leakage of PHTS(Primary Heat Transport System) by an internal event

These accidents, even in high PDS accidents, are selected under as various conditions as possible; vessel failure, CFVS operation and hydrogen generation rate.

Mass and energy release rate during accident were the results from the MAAP-ISAAC analysis. Figure 3 shows the designated location of the mass and energy release in the geometric model. Figure 4 typically shows the released rate of water and each gases of Case3 accident.



(a) Side view (b) Top view

Fig. 3 Mass and energy release locations

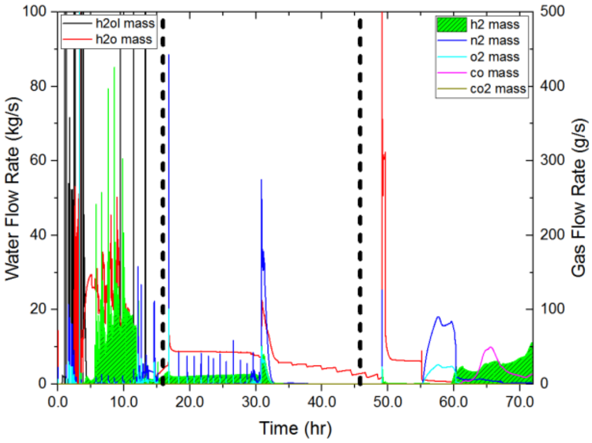


Fig. 4. Released rate of water and each gases for Case3 accident

3. Analysis Results

A total of four accident scenarios were analyzed and in the MAAP-ISAAC analysis, a period of 72 hours was performed. For efficient analysis, however, analysis of GASFLOW-MPI was performed by separating the in- and ex-vessel release mode. Table 2 summarizes the analysis periods for each accident.

Table 2: Accidents and Analysis Period

Accidents	Release mode	Analysis Period
Case1	In-vessel	0 ~ 22,350 (6.2 hr)
	Ex- vessel	155,000 (43.0 hr) ~ 249,163 (69.2 hr)
Case2	In- vessel	0 ~ 46,478 (12.9 hr)
	Ex- vessel	165,000 (45.8 hr) ~ 259,200 (72 hr)
Case3	In- vessel	0 ~ 57,188 (15.9 hr)
	Ex- vessel	155,000 (45.8 hr) ~ 259,200 (72 hr)
Case4	In- vessel	0 ~ 45,851 (12.7 hr)
	Ex- vessel	Not analyzed

3.1 In-vessel Release Period

The pressure behavior during the in-vessel release period showed less than 300 kPa in all accidents except Case3(400 kPa) accident. For temperatures Case3 also showed the highest value (410 K). Figure 5 shows the typical temperature contour map of Case2 accident at about 12.9 hours after the accident. As shown in the figure, the upper space of the containment building shows a relatively high spot compared to the average temperature over the containment building, which is caused by hydrogen and oxygen reaction with PARs operation.

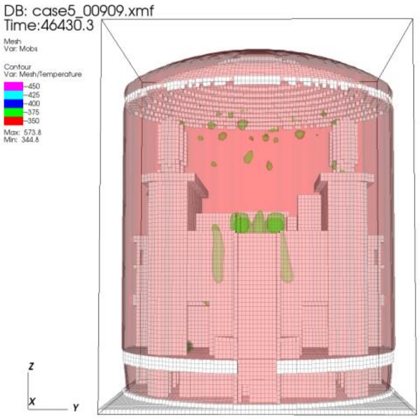


Fig. 5. Temperature contour map for Case2 accident

Before the accident, the containment atmosphere is filled with humid air (mainly steam and oxygen). Along with accident, large quantities of steam are released during the beginning stage and hydrogen release follows approximately five hours later. According to hydrogen accumulation in upper containment space, the PAR begins to operate and soon after, the incremental rates of pressure, temperature and hydrogen fraction are gently reduced. All accident analysis shows the almost same behavior. As an example, figure 6 shows the hydrogen fraction contour map after 12 hours of Case4, and the GASFLOW-MPI calculation detects well the low hydrogen fraction spots at the location where the PAR is installed.

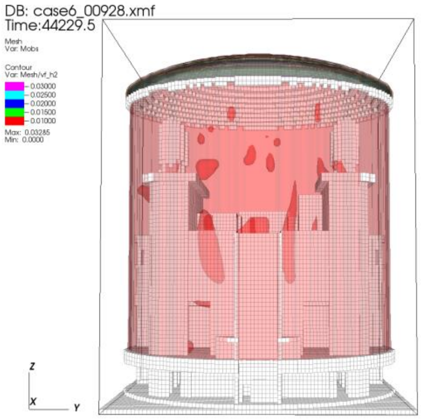
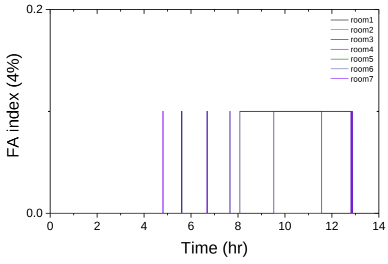
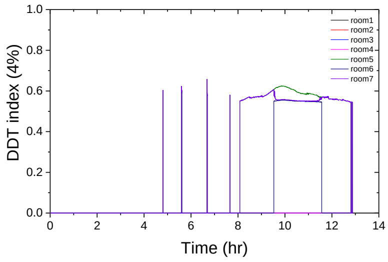


Fig. 6. Hydrogen volume fraction contour map for Case4 accident

The FA Index and DDT Index, which represent hydrogen threats, shows the value from 0.1 to 0.6 but were lower than 1 and thus no hydrogen threat has been confirmed during in-vessel release period. As an example, figure 7 shows the FA and DDT indices in Case3. The same trend was identified in the rest of the accident analysis.



(a) FA index



(b) *DDT index*

Fig. 7 FA and DDT index of Case3 accident

3.2 Ex-vessel Release Period

Ex-vessel release analysis was performed except for the Case4 accident because of the no failure of vessel during this period. During the in-vessel release, a large proportion of hydrogen and oxygen due to PAR operation was depleted so that ex-vessel release analysis begins with the initial condition of very high steam fraction. The main ex-vessel hydrogen release starts between 52 and 60 hours and because there is no additional oxygen release before this time, the oxygen fraction is very low and the steam is relatively very high. For this reason, the operating conditions of PAR and hydrogen threat have not been detected during the ex-vessel release.

4. Conclusions

This research presents and discusses the detail results of three-dimensional analysis of hydrogen hazard assessment in the containment building of CANDU type NPP using GASFLOW-MPI code. Input model of GASFLOW-MPI code were prepared well and the analyses of the four selected accident scenarios have been performed during two separate periods; in-vessel and ex-vessel release. The initial and boundary conditions of analysis were taken from the MAAP-ISAAC analysis that is performed separately.

Analysis of the in-vessel release showed no hydrogen threats with the operation of PAR and no severe stratification because of well mixed containment atmosphere condition derived by strong discharging momentum. The concentration of hydrogen is also maintained at less than 3% in all areas. Both DDT index and FA index showed much lower values than the threat level. Ex-vessel release analysis begins in environments where there is little fraction of hydrogen and oxygen and high steam fraction, because the operation of PAR during in-vessel release period depleted hydrogen and oxygen. On the other hand, in the ex-vessel release analysis, temperature and gas species stratification have been detected clearly. Nevertheless, the probability of combustion was never found in all analyses and it even fell short of the PAR operating conditions.

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