EFFECTS OF SPRAY MODES ON HYDROGEN RISK IN A CHINESE NPP

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ABSTRACT

Three dimensional CFD code, GASFLOW, is applied to analyze the hydrogen risk for Qinshan-II Nuclear Power Plant (NPP) in China. In order to check the effects of spray modes on hydrogen safety, three different spray strategies are selected, i.e. without spray, with direct spray and with both direct and recirculation spray. The obtained results are compared between different cases, in the aspect of thermal hydraulics behavior and hydrogen risk. The effect of the direct and recirculation spray on hydrogen risk is discussed.

1. INTRODUCTION

During the severe accident of water-cooled reactors, hydrogen can be generated by the metal-steam reaction. The generated hydrogen will be released into the containment and forms the combustible or even detonable gas mixture. As one of the mitigation measures for severe accidents in Qinshan-II NPP, the containment spray systems are designed to activate when the pressure inside the containment value reaches the threshold value. The spray operation affects the hydrogen behavior inside the containment in two aspects. In one respect, the operation of containment spray systems reduces the steam concentration in the atmosphere and, in the same time, increases the hydrogen concentration which augments hydrogen combustion or detonation possibility. In the other respect, the containment spray promotes the atmosphere mixing and leads to more uniform distribution of the hydrogen concentration.

The effect of containment spray on the hydrogen behavior is traditionally analyzed with lumped-parameter codes which provide simplified spray model. In this study, three dimensional CFD code GASFLOW (Travis, 1998) is utilized to evaluate the effect of containment spray on the hydrogen risk in Qinshan-II NPP. In the evaluation, a case in which the containment spray is not activated is simulated as the Base Case. Two cases with different containment spray operation strategies are analyzed. One of them considers only the direct spray (indicated as Spray Case A, hereafter), while the other simulates the whole spray operation, including the direct and recirculation spray (indicated as Spray Case B, hereafter).The results are analyzed and compared in different respects.

2. GEOMETRY MODEL AND PHYSICS MODELS

The containment in Qinshan-II NPP consists of a cylindrical part and a spherical dome. The total height is about 60 m, and the diameter about 38 m (Zhang, 2005). The containment model was established under cylindrical coordinates. The compartments mainly locate below the operation deck which is at the height of 20 m. Two steam generator (SG) towers are arranged, and two reactor coolant pump (RCP) rooms are also symmetrical. These rooms along with two safety injection tank (SIT) rooms are on the deck at 4.5 m, but the top of rooms reaches different height. The pressurizer (PZR) room in the neighbor of a SG tower is at the height between approximately 11 to 29 m. The PZR relief tank room is at 0 m and under the PZR room. The refueling pool locates at the height between 6 to 20 m. It connects with the reactor cavity which is in the center of the containment and reaches to the containment wall in the radial direction. There are some other small rooms accommodating the valve, piping and heat exchangers in the floor below zero meter and the zero meter floor. Generally, all the above rooms mentioned are inside a cylindrical missile shielding wall which protects the containment from ejected missiles. Above the operation deck, it is much emptier. Only the SG towers and PZR room extend to the height beyond the deck. And a crane is installed in the dome. GASFLOW can generate structural mesh in both Cartesian and cylindrical coordinates. According to the characteristics of the containment geometry, the cylindrical coordinates is selected, and the small mesh sizes are utilized in the lower part of the containment to satisfy the requirement for complex structure description, while coarser mesh is used in the upper region.

In order to mitigate the hydrogen risk during severe accidents, 22 Siemens Passive Automatic Recombiners (PAR) are installed in the containment compartments. Table 1 lists the position and type of the PAR. Each PAR is simulated with a single mesh cell. The recombination rate is calculated with a correlation provided by Siemens.

Two separated containment spray systems are installed. During the severe accidents, the containment can be depressurized with the operation of only one spray system, according to the design of the spray systems. The other one is redundant. Both systems include two nozzle rings, as indicated in Fig. 1, on which attach about 250 nozzles. The mass flow is uniformly distributed to the nozzles. Heat exchangers in the systems control the temperature of spray water. The spray systems are designed to operate in two modes: direct spray mode and recirculation spray mode. The direct spray starts while the pressure in the containment reaches 2.36 bar and pumps water from the refueling tank. In the direct spray mode, the temperature at the nozzle outlet is about 20 to 40 ^{o}C and, in this study, given to be 27^{o}C. In 30 minutes, the water in the refueling tank will be used up, and the spray switches to operate in recirculation mode. In the recirculation mode, the spray water is pumped from the sump inside the containment. And the temperature at the nozzle outlet is designed to be 40 to 120 ^{o}C and given as 77^{o}C in the simulation. The total spray mass flow rates in direct and recirculation spray modes are, respectively, 814 and 1050 ton per hour (Zhang, 2005).

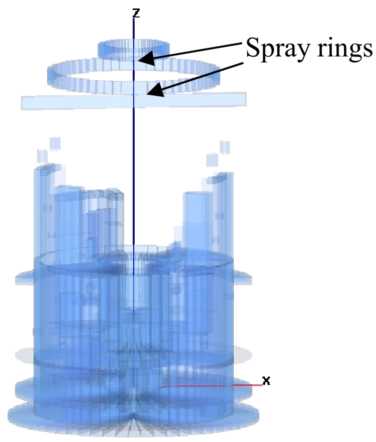


Fig. 1 Containment geometry model

Table 1 Arrangement of recombiners

Location	Type	No.
PZR Relief Tank Room	FR90/1-1500	3
Surge Line Room	FR90/1-960	1
PZR Room	FR90/1-960	1
No. 1 SG Compartment	FR90/1-1500	3
No. 2 SG Compartment	FR90/1-1500	3
No.1 RCP Room	FR90/1-960	1
No.1 RCP Room	FR90/1-960	1
SIT Room	FR90/1-960	1
Dome region	FR90/1-1500	4
Annular Compartment	FR90/1-1500	4

GASFLOW provides two approaches for two phase flow simulation (Travis, 1998). While the spray is not activated in a simulation, the homogeneous equilibrium approach is applied automatically, which assumes that the liquid and gas phase are in thermodynamic and mechanical equilibrium. Because the spray operation introduces strong transient thermodynamic non-equilibrium inside the containment, in order to exactly simulation the interaction of between the two phases during spray, GASFLOW offers another approach which considers the thermal non-equilibrium, but still neglect the difference of mechanical behavior between the liquid and gas phase. GASFLOW spray model has been validated with TOSQAN experiment and gives satisfactory prediction of the experiment data (Kim, 2006).

3. SOURCE TERM AND SPRAY OPERATION

The source term for this analysis was obtained by scaling from GKN surge line Large Break LOCA (LBLOCA) source term given in reference (Royl, 2000), as shown in Fig.2. The break locates low in the SG tower. In the beginning of the accident, a large amount of water is discharged into the containment. After the blowdown, the water flow rate decays, while the water temperature increases. The hydrogen release starts at about 1400 s. About 270 kg hydrogen is released into the containment during the first 7000 s. At 5932 s, a strong hydrogen release peak is produced due to an enhancement of steam/zirconium reaction after the failure of the core support. Fig. 2 indicates also different spray periods which is determined according to the pressure variation obtained in the Base Case. In less than 100 seconds, the pressure reaches the threshold value and the spray starts.

4. RESULTS

4.1 Integral effects

In the Base Case, the average pressure and temperature variation in the atmosphere inside the containment is dominated by water injection into the containment, as indicated by Fig. 3 and 4. In all the cases, a steep pressure rise occurs after the blowdown. The spray activation dramatically depressurizes the containment by introducing large amount of bulk condensation in short time, as show in Fig. 5. In this accident scenario, the steam discharge prolongs beyond the direct spray phase, so that, in the Spray Case A, pressure and temperature buildup in the containment atmosphere occurs after the spray shutdown. A slight pressure and temperature increase after the switch of spray mode in the Spray Case B, because the recirculation spray water is at a higher temperature than the direct spray. Generally, the recirculation spray keeps the pressure and temperature inside containment at a constant level.

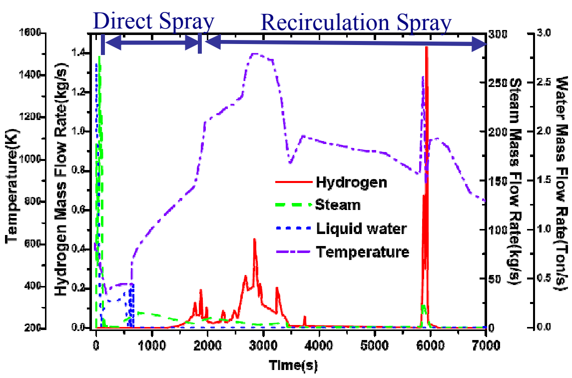


Fig. 2 Source term and spray activation

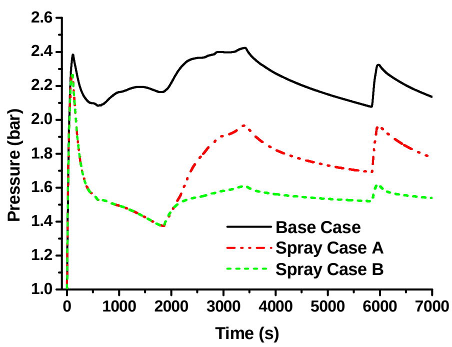


Fig. 3 Pressure variation in three cases

4.2 Condensation

As shown in Fig. 5, heavy condensation occurs on the water droplets during the direct spray mode, while, in the recirculation spray phase of Spray Case B, the evaporation of spray droplets is observed. Due to the evaporation, the atmosphere temperature is well controlled. The evaporation of spray water is an essential issue from the aspect of hydrogen safety because it increases the steam concentration and builds up inertial atmosphere. Hence, the recirculation spray can help both mixing and inertization. It can also be concluded that besides controlling the pressure and temperature of the containment atmosphere, in the aspect of hydrogen safety, the outlet temperature of recirculation spray can be optimized to enhance the evaporation of spray droplets. In the practical hydrogen safety analysis, it is crucial to provide the exact spray water temperature.

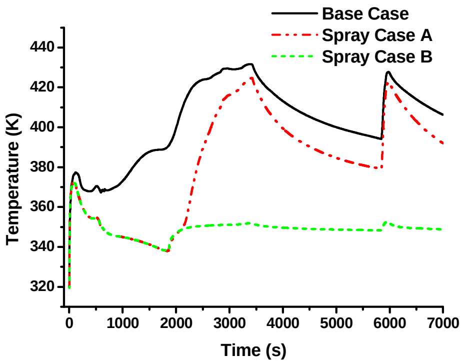


Fig. 4 Average temperature variation

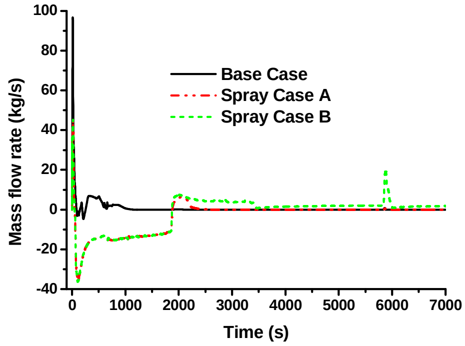


Fig. 5 Bulk mass change due to phase change

Besides the bulk condensation, the condensation on the structure surface is also enhanced at the beginning of spray operation, as shown in Fig. 6 and 7. Before the spray activation, the hot steam clouds are not well mixed with the containment atmosphere, and do not have easy access to the cold surface, which leads to comparatively low surface condensation rate. The spray operation introduces strong mixing inside the containment, so that the steam clouds get much easier access to the cold surfaces. The increased surface condensation rate helps the containment depressurization. The strong bulk and surface condensation shortly after the spray activation decreases the steam concentration dramatically. After that, the surface condensation is suppressed during the direct spray phase in the spray cases, which resists the temperature rise in the structures. After the shutdown of direct spray, the surface condensation rate in the Spray Case B shows to be higher than that in the Spray Case A, which benefits from the enhancement of mixing. Compared with the Base Case, a slightly high surface condensation rate is observed in both spray cases due to the cold structures.

Besides the condensation/evaporation on the surfaces, the radiation and convection are two important heat transfer manners between the atmosphere and structures. As shown in Fig. 6, in all the cases the condensation dominates the heat transfer at the beginning of the blowdown. In the Base Case, convective and radiation heat transfer becomes important as the accident develops. While in the spray cases, it can be noted that the convective and radiation heat transfer is negligible during the spray operation periods, because the temperature difference between the atmosphere and structures is small.

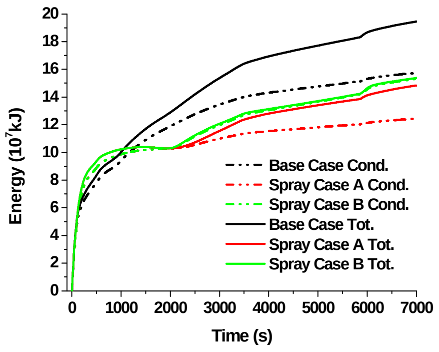


Fig. 6 Energy absorption by structures

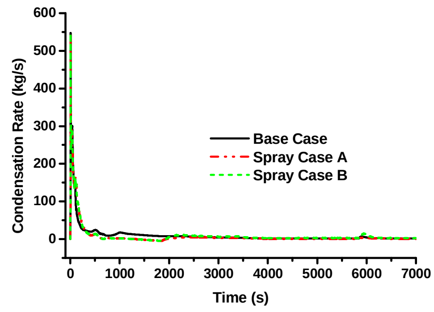
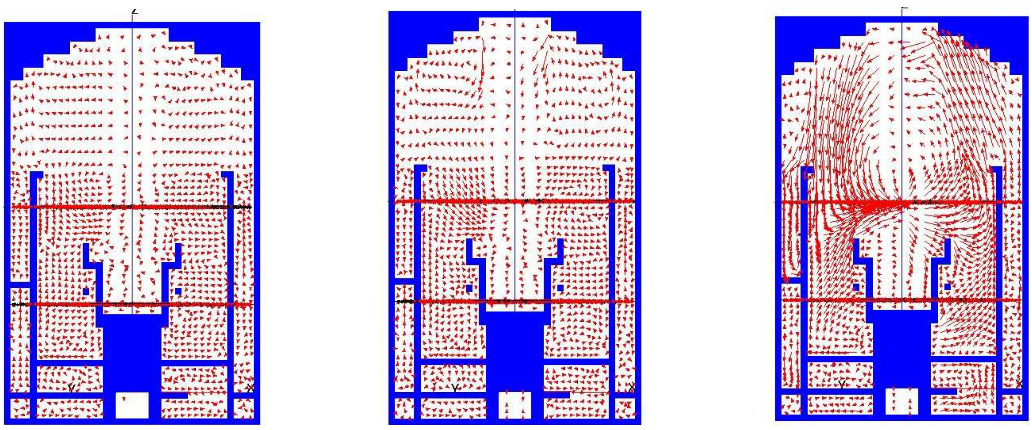


Fig. 7 Structure surface condensation rate

4.3 Flow field

Fig. 8 presents the flow fields after the heavy hydrogen release period in three cases. In the Base Case (Fig 8a) and Spray Case A (Fig 8b), the magnitude of velocity is generally less than 0.5 m/s, and a downward flow is observed near the structure surfaces, due to the steam surface condensation or convective heat transfer. A much stronger flow is observed in the Spray Case B (Fig. 8c). A large-scale vortex shows in the dome, in which the gas flows upward in one side of dome and flows downward in the other side of dome. Fig. 9 indicates the density distribution and velocity field. It can be found that the density of the downward flow is larger than that of the upward flow. As has mentioned in paragraph 2, GASFLOW spray model uses mechanical equilibrium assumption while dealing with the two-phase flow. Actually, the heavy liquid phase is more inclined to drop down than the gas phase. The assumption inevitably leads to an artificial flow. The actual situation is that the gas phase is accelerated by the friction between the two phases and also by natural convection. In this case, the mixing flow inside the containment should not be as strong as in the obtained results.

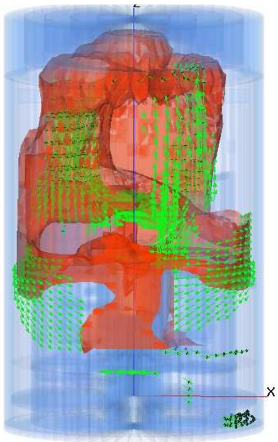


a) Base Case t=6015s b) Spray Case-A t=6010s c) Spray Case-B t=6010s

Fig. 8 Flow fields after the hydrogen release peak

4.4 Hydrogen recombination

According to the Siemens recombiner correlations (Travis, 1998), the recombination rate depends on the pressure and inlet hydrogen and oxygen concentration. Although the pressure discrepancy is large between the analyzed cases, as mentioned in section 4.1, the total recombination rate of 22 PARs doesn't show great difference in the three cases, as indicated in Fig.10. Generally, the sum of recombination rate develops in the same trend. Following the hydrogen release into the containment, the recombiners start up as the inlet hydrogen concentration reaches the threshold (2 vol. %). Due to the increase of hydrogen concentration, the hydrogen recombination rate ascends. At about 3500 s when the hydrogen release interrupts, the recombination rate reaches stable value. From 3500 s to 5900 s when the hydrogen release is discontinuous and at a quite low rate, the recombination rate reduces slowly. During this period, oscillation of recombination rate occurs in Spray Case B because strong flow cause by the spray brings the variation of hydrogen concentration at the inlet of recombiners. After 5900 s, the spray cases show a higher recombination rate than the Base Case due to a higher hydrogen concentration. Here, the recombiner volume flow rate is deduced from the recombination rate obtained from Siemens correlations. In this case, the recombination rate is affected only by the gas species concentration and pressure at the inlet of recombiner. BMC Zx tests include several recombiner tests during spray (OECD/NEA, 1999). The results suggest an increase of the volume flow rate through recombiners and recombination rate due to spray. In order to integrate this effect into simulation, another approach which obtain the recombiner flow rate by coupling the flow in the containment and the flow in recombiner.



Red: $\rho \geq 2\ \mathrm{g/cm^3}$, **Green:** $u \geq 4\ \mathrm{m/s}$

Fig. 9 Density cloud and velocity in Spray Case B at 6010 s

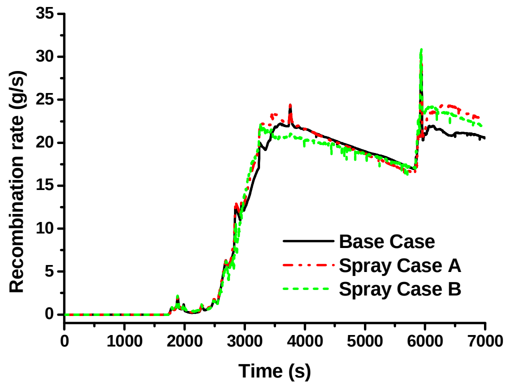
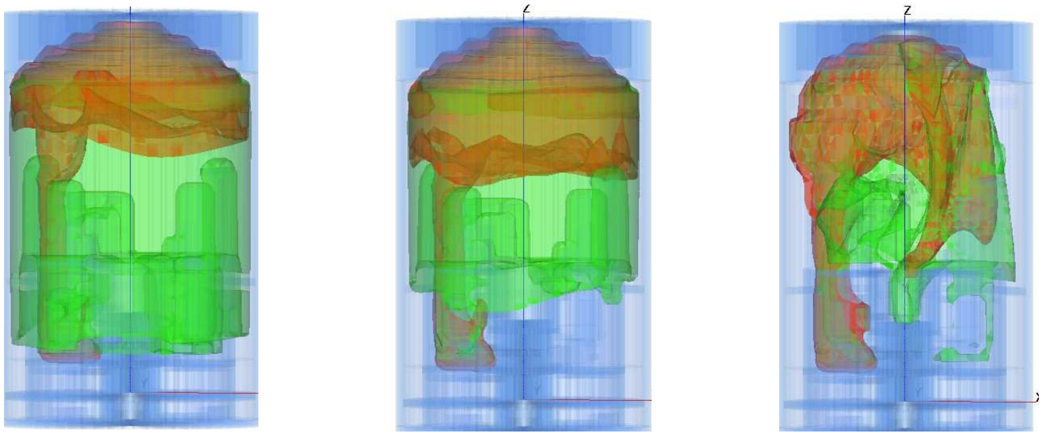


Fig. 10 Recombination rate

4.5 Hydrogen and steam distribution

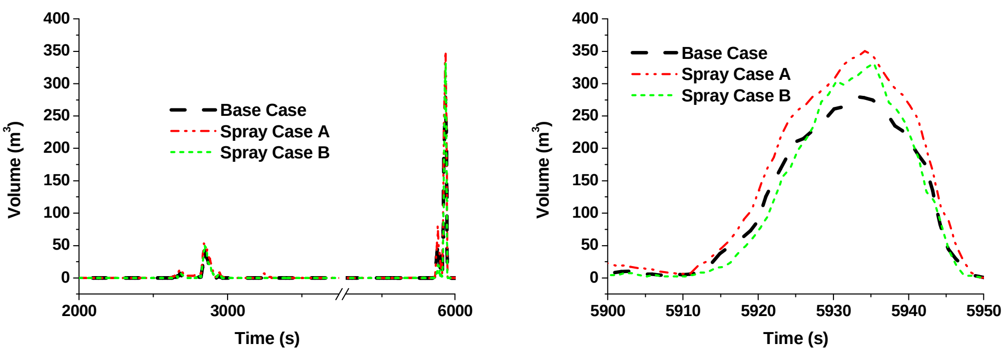
The hydrogen release can generally be divided into two periods. The first period extends from 1400 s to 3500 s. In this period produces an atmosphere with a hydrogen concentration averagely higher than 3%, but the flammable clouds (of hydrogen concentration above 4%) rarely appear. Due to the hydrogen-oxygen recombination, the hydrogen concentration can be reduced below 3% before the second release period. The hydrogen concentration stratification is always obvious in both Base Case and Spray Case A. The clouds of high hydrogen concentration can always be enveloped by steam-rich clouds which provide an inertial atmosphere and prevents the early combustion. Fig. 11 presents the hydrogen and steam clouds at the moment when hydrogen release mass flow rate reaches the peak. 4% hydrogen cloud in Spray Case A is of the biggest size among the three cases. Compared with the Base Case, the steam concentration is low in the spray cases, which increases the hydrogen fraction. As discussed in section 4.3, the strong flow inside the containment promotes the mixing, so the hydrogen stratification is not observed. Hence, the direct spray reduces the steam volume fraction and increases the hydrogen volume fraction correspondingly, while the recirculation spray does not raise an increase of hydrogen concentration, while resisting the hydrogen concentration stratification.



a) Base Case at 5944 s   b) Spray Case A at 5940 s   b) Spray Case B at 5940 s

Red: 4%H_2 **Green:** 40% steam   **Red:** 4%H_2 **Green:** 30% steam   **Red:** 4%H_2 **Green:** 30% steam

Fig. 11 Hydrogen and steam clouds at the moment when hydrogen release reaches peak value



a)   b)

Fig. 12 The volume of sigma clouds

In order to analyze the characteristics of the hydrogen mixture in the containment, the volume of sigma cloud is used in this study. The sigma cloud is a volume of the hydrogen mixture with a sigma index larger than one, where the sigma index is defined as an expansion ratio of a flammable mixture by a combustion divided by its critical value which is obtained from experimental data. (Dorofeev, 1999) Fig. 12 presents the evolution of total sigma volume inside the containment in three cases. The peak sigma volume in the spray cases is larger than that in the Base Case, and the peak sigma volume in Spray Case B is between that in the Base Case and the Spray Case A. It can be concluded that the direct spray phase deteriorate the hydrogen risk, while the recirculation spray phase which helps mixing can mitigate the hydrogen risk.

5. CONCLUSION

The results show that the direct spray is not enough to suppress the temperature and pressure increase. After the direct spray, a sharp increase in temperature and pressure can be found, which implies the potential of the containment overpressure. Furthermore, the direct spray introduces large amount of bulk condensation and also promotes the surface condensation at the beginning of the operation, which is beneficial for the depressurization. The heavy condensation induced by the direct spray can increase the hydrogen risk. The recirculation spray promotes the mixing of atmosphere and introduces bulk evaporation which helps build an inertial atmosphere. The hydrogen stratification is diminished by the recirculation spray. And the potential of flame acceleration is increased due to the direct spray and mitigated by the recirculation spray. The efficiency of recombiner is not essentially affected by the depressurization due to the spray.

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