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Analysis of hydrogen risk mitigation with passive autocatalytic recombiner system in CPR1000 NPP during a hypothetical station blackout

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ABSTRACT

Hydrogen safety has attracted extensive concern in severe accident analysis especially after the Fukushima accident. In this study, a similar station blackout as happened in Fukushima accident is simulated for CPR1000 nuclear power plant (NPP) model, with the computational fluid dynamic code GASFLOW. The hydrogen risk is analyzed with the assessment of efficiency of passive autocatalytic recombiner (PAR) system. The numerical results show that the CPR1000 containment may be damaged by global flame acceleration (FA) and local detonation caused by hydrogen combustion if no hydrogen mitigation system (HMS) is applied. A new condensation model is developed and validated in this study for the consideration of natural circulation flow pattern and presence of non-condensable gases. The new condensation model is more conservative in hydrogen risk evaluation than the current model in some compartments, giving earlier starting time of deflagration to detonation transition (DDT). The results also indicate that the PAR system installed in CPR1000 could prevent the occurrence of the FA and DDT. Therefore, HMS such as PAR system is suggested to be applied in NPPs to avoid the radioactive leak caused by containment failure.

1. Introduction

Studies on possible consequences of core meltdown in severe accidents have demonstrated that hydrogen combustion is one of the main contributors to the containment early failure (Breitung and Royl, 2000). The hydrogen explosion in Fukushima accident has aggravated public panic for radioactive leak and reduced public confidence in nuclear safety.

Analysis of the hydrogen safety during severe accidents with lumped parameter (LP) codes has been carried out for many years. Some LP codes such as CONTAIN and MAAP have been applied in nuclear power plant (NPP) models to analyze the hydrogen distribution, combustion and mitigation (Kim et al., 1996; Watada and Furuta, 1996). Recently, the computational fluid dynamic (CFD) codes are used in the hydrogen risk analysis during severe accidents to obtain localized detailed information and supplement the results of LP codes which focus on global or averaged effect (Royl et al., 2000). Some empirical and semi-empirical models, such as condensation model (Martín-Valdepeñas et al., 2005) and PAR model (Bachellerie et al., 2003), are applied in CFD codes for the analysis of the containment scale. In engineering application, these models could give satisfactory results and save computational resources.

GASFLOW is a best-estimate three dimensional (3D) field code developed by Forschungszentrum Karlsruhe and Los Alamos National Laboratory for predicting the transport, mixing, and combustion of hydrogen and other gases in nuclear reactor containment during severe accidents (Travis et al., 1998). This paper presents the study of hydrogen risk in containment and evaluation of passive autocatalytic recombiner (PAR) system efficiency in CPR1000 NPP during station blackout as happened in Fukushima accident. Since the effect of steam condensation on the hydrogen behavior is significant (De la Rosa et al., 2009), the development of condensation model in GASFLOW is also performed. The new model is validated using the results of international benchmark and applied in hydrogen risk analysis during hypothetical severe accident.

2. Analytical methods

2.1. Sigma and lambda criteria

After igniting the flammable gas mixture, the slow turbulent flame will propagate along the hydrogen concentration gradient towards higher hydrogen concentration regions with intense turbulence. Flame acceleration (FA) may result in a deflagration to detonation transition (DDT). A large number of experiments were conducted to obtain the general scaling laws of FA and DDT by Forschungszentrum Karlsruhe and Kurchatov Institute (Dorofeev et al., 1996; Breitung et al., 2005). Based on these experimental

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results, sigma criterion is developed and used in GASFLOW to obtain a conservative estimate of FA:

$$\sigma_{index} = \frac{\sigma(x_{H_2}, x_{H_2O}, x_{O_2}, T)}{\sigma_{critical}(x_{H_2}, x_{O_2}, T)} \tag{1}$$

where x_{H_2}, x_{H_2O}, x_{O_2} are the average concentrations of hydrogen, steam and oxygen within the compartment, respectively, T is the average temperature, $\sigma(x_{H_2}, x_{H_2O}, x_{O_2}, T)$ is the expansion ratio of unburned to burned gas at constant pressure in specified compartment and $\sigma_{critical}(x_{H_2}, x_{O_2}, T)$ is the critical expansion ratio of gas mixture acquired from the experiments. When $\sigma_{index} \geqslant 1$, there is a potential for FA, whereas for $\sigma_{index} < 1$, FA can be excluded.

In GASFLOW, the potential of DDT is determined by the following lambda criterion:

$$R = \frac{D}{7\lambda(x_{H_2,dry}, x_{H_2O}, T)} \geqslant 1 \tag{2}$$

$$D = V^{\frac{1}{3}} \tag{3}$$

where R is the lambda index, $x_{H_2,dry}$ is the dry hydrogen concentration within the compartment, D is the characteristic size of the reaction cloud, $\lambda(x_{H_2,dry}, x_{H_2O}, T)$ is the average detonation cell width of the gas mixture and V is the volume of cloud above the lower flammability limit. When $R \geqslant 1$, there is a potential for DDT.

2.2. Improvement of condensation model in GASFLOW

In many thermal hydraulic codes, the empirical correlations and the heat and mass transfer analogy (HMTA) are two most important methods to calculate the steam condensation rate (De la Rosa et al., 2009). The empirical correlations, such as Uchida correlation and Tagami correlation, are based on the experimental data in which the total heat transfer coefficient is obtained as a function of non-condensable gases mass fraction in the bulk. Application of these empirical correlations is restricted within the experimental range. In current GASFLOW version, HMTA is applied and the convective heat transfer coefficient is calculated by modifying wall law and empirical multiplication factor (Travis et al., 1998).

In GASFLOW, the condensation mass flow rate on structure surface is calculated:

$$\dot{m}_{cd} = K_{cd}\ \Theta\ (\rho_{v,\infty} - \rho_{v,sat})A_s \tag{4}$$

where $\dot{m}_{cd}$ is the condensation rate, Θ is the correction factor accounting for suction effect, $\rho_{v,\infty}$ is the vapor density in the bulk, $\rho_{v,sat}$ is the saturated vapor density on structure surface, A_s is the surface area, and K_{cd} is the mass transfer coefficient of condensation and evaporation. The factor Θ accounts for the suction effect with Bird factor (Bird et al., 1960):

$$\Theta = \frac{\log(M+1)}{M} \tag{5}$$

$$M = \frac{X_{v,I} - X_{v,\infty}}{1 - X_{v,I}} \tag{6}$$

where $X_{v,I}$ is the steam mole fraction at the interface, $X_{v,\infty}$ is the steam mole fraction in the bulk. $\rho_{v,sat}$ is determined by the saturation pressure $p_{sat}(T_I)$ and surface temperature T_I at the interface:

$$\rho_{v,sat}(T_I, p_{sat}(T_I)) = \frac{p_{sat}(T_I)}{R_v T_I} \tag{7}$$

The HMTA with empirical correlation of Chilton–Colburn is applied to obtain the mass transfer coefficient:

$$K_{cd} = \frac{h_{cv}}{\rho C_p}\left(\frac{\mathrm{Pr}}{Sc}\right)^{\frac{2}{3}} \tag{8}$$

where h_{cv} is the convective heat transfer coefficient, C_p is the specific heat.

It should be observed in Eq. (8) that the convective heat transfer coefficient is important for the calculation of condensation mass transfer coefficient. In current GASFLOW version, a modified wall law is applied to solve the convective heat transfer coefficient. The modification is conducted because the cell size of containment scale with GASFLOW is very large (around 0.5–1.0 m^3) and it is difficult to locate the first grid point in the logarithmic region. In order to avoid the application of wall law and empirical multiplication factor, the McAdams correlation (Herranz et al., 1998) is coupled in GASFLOW to calculate the convective heat transfer coefficient. In McAdams correlation, Nusselt number is calculated by Grashof number and Prantl number:

$$Nu = 0.13 Gr^{\frac{1}{3}} \mathrm{Pr}^{\frac{1}{3}} \tag{9}$$

The Grashof number is reformulated as a function of density difference instead of temperature difference in the boundary layer with sharp composition gradients:

$$Gr = \frac{g\rho_\infty(\rho_I - \rho_\infty)L^3}{\mu^2} \tag{10}$$

where g is the acceleration of gravity, ρ_∞ is the mixture density in the bulk, ρ_I is the mixture density at the interface, L is the characteristic length scale, μ is the dynamic viscosity of gas mixture. And the convective heat transfer coefficient h_{cv} is expressed as follows:

$$h_{cv} = 0.13(g\rho_\infty(\rho_I - \rho_\infty)\mathrm{Pr})^{\frac{1}{3}}\mu^{-\frac{2}{3}}\lambda \tag{11}$$

where λ is the thermal conductivity of gas mixture.

The convective heat transfer coefficient calculated by McAdams correlation does not depend on the characteristic length scale and the McAdams correlation is suitable for regimes of natural circulation of containment scale, with Rayleigh number ranges from 10^9 to 10^{12}. Moreover, the variability of gas properties which is important for the application of McAdams correlation is taken into account in GASFLOW, such as the variability of dynamic viscosity, thermal conductivity and specific heat. According to the theory of the condensation on the liquid film in the presence of non-condensable gases, the condensation mass flow rate is obtained (Kudriakov et al., 2008):

$$\dot{m}_{cd} = K_{cd}\ \Theta\ (\rho_{v,\infty} - \rho_{v,sat})A_s\left(\frac{1}{1 - Y_{v,\infty}}\right) \tag{12}$$

where $Y_{v,\infty}$ is the steam mass fraction. The condensation model based on the McAdams correlation and Chilton–Colburn correlation in HMTA is identified as "McAdams–Chilton model", and the current condensation model in GASFLOW is referred as "wall law-Chilton model".

The MICOCO test (Blumenfeld and Paillère, 2003) and ISP 47 test (Studer et al., 2007) performed in the MISTRA facility are chosen as validation exercises for McAdams–Chilton model in GASFLOW. Since this work focus on the air–steam or air–steam–helium steady state in experiment, we set the thermodynamic conditions of steady states directly to save the CPU time (Kudriakov et al., 2008). Because of the discrepancy between experiment and numerical simulation, a new steady state will be obtained in the calculation when the injected steam mass flow rate is equal to the steam condensation rate on the structures. The validation of key variables in steady states is shown in Tables 1 and 2. In the MICOCO test with steam injection, the wall law-Chilton model overestimates the average pressure by 3.6% and underestimates the average temperature by 1.8%. And the McAdams–Chilton model decreases the differences to 1.7% and 1.0%, respectively. Especially, the distribution of condensation mass flow rates on