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Hydrogen concentration variation and examination of PAR installation in reactor containment building during hydrogen release from different direction failure places

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HIGHLIGHTS

- Hydrogen distribution inside a nuclear containment building during SBLOCA is analyzed.
- Mixture concentration variation with time is analyzed at several locations.
- Performance of passive autocatalytic recombiner (PAR) is examined.

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ABSTRACT

Concentration on a hydrogen explosion mitigation strategy increased after the accident in Fukushima. A passive autocatalytic recombiner (PAR) is considered as the most realistic mitigation technology during a severe accident where electric power is lost. Hydrogen distribution and concentration might be accurately predicted because PAR must be installed in a place having a proper amount of hydrogen in order to produce positive performance. In this paper, hydrogen distributions and concentrations were predicted and analyzed during hydrogen release from different direction failure places, and then PAR installation was examined. The result shows that the hydrogen concentrations are randomly changed in the containment overall, and the behavior of hydrogen in the case of upper part failure is completely different from the case of a side part failure. It is expected that PAR works well in the area among small compartments located at the lower part of the containment building; however, the performance of PAR installed on another area is inferior.

1. Introduction

Hydrogen safety has been studied in a nuclear plant, and its study has been further considered since the Fukushima accident in 2011. Many studies have been performed on hydrogen distributions and mitigation strategies (Park et al., 1994; Kim et al., 2005a,b, 2006; Lee et al., 1997; Heitsch et al., 2010; Royl et al., 2000; Rohde et al., 1992) and many technologies have been developed in order to control or remove hydrogen. An igniter is a tool widely used to reduce hydrogen released (IAEA, 2001; Heck et al., 1995; Vlachos, 1996). This item is a simple and low-cost technology, and is a useful tool during normal conditions. However, it is useless during severe blackout accidents because it needs an electric power supply to function.

Another instrument is the passive autocatalytic recombiner (PAR), which reduces hydrogen through the chemical reaction of hydrogen and oxygen without supplied electric power. This method has been considered an appropriate method when a severe accident takes place because it does not need electric power. Many studies have been performed on hydrogen's reduction rate, temperature, size, and so on (Kim et al., 2001; Reinecke et al., 2004, 2005, 2008, 2010; Fujii and Fujimoto, 1999; Blanchat and Malliakos, 1999, 2000; Huang et al., 2011; Prabhudharwadkar and Iyer, 2011; Mori et al., 1977; Dewit et al., 1997; Appel et al., 2002; Fineschi et al., 1996; De Boeck, 2001; Payot et al., 2012; Jiménez et al., 2007; Treviño, 2011; Prabhudharwadkar et al., 2011; Bachellerie et al., 2003; Deng and Cao, 2008). The hydrogen reduction rate at the dry condition of air and hydrogen mixture is different from that at wet condition. The reduction rate is reduced through the increase of steam fraction (Payot et al., 2012; Blanchat and Malliakos, 2000). The temperature on the surface of the catalyst can be increased beyond the combustion limit of the hydrogen-air

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Nomenclature

$L_{concrete}$	wall depth of containment building
h_{in}	convective heat transfer coefficient inside
h_{out}	convective heat transfer coefficient outside
l_{fg}	latent heat
$k_{concrete}$	conduction heat transfer coefficient of concrete
U	overall heat transfer coefficient
$\dot{m}$	steam condensation rate
T	temperature
T_{sat}	saturation temperature
ρ	gas density
U_j	velocity tensor
S	source term
t	time
Φ	properties
k	turbulent kinetic energy
w	turbulent frequency

mixture (Jiménez et al., 2007; Reinecke et al., 2008, 2010; Treviño, 2011; Prabhudharwadkar et al., 2011).

A lot of steam and water are released when a severe accident takes place in a nuclear plant, which means that the operation conditions of a PAR is not clear. Therefore the exact prediction of fractions of hydrogen, air, and steam mixture is needed in order to install the equipment in suitable places.

The generation mechanism of hydrogen during a loss-of-coolant-accident (LOCA) was reported in (Shapiro and Moffette, 1957). When LOCA takes place, the coolant does not supply to the nuclear reactor vessel. In the vessel the temperature continuously increases, and the cooling water vaporizes. At high temperature, the steam reacts with zirconium coating nuclear fuel rods, and a lot of hydrogen is generated (Bachellerie et al., 2003; Deng and Cao, 2008; Morfin et al., 2004). Additional amount of hydrogen is generated with the reaction of the steam and steel structures or nuclear fuel. The generated hydrogen is released though the failure of pressurized pipe, which is called the small breakup loss of coolant accident (SBLOCA) (Kim et al., 2004; KAERI, 2009).

In order to effectively remove the hydrogen released, the hydrogen distribution and concentration variation must be predicted carefully overall the containment building. Afterward, the positions for installing PAR can be decided. Many studies have been performed on hydrogen behavior to find out where and when hydrogen is gathering. However, the distribution of hydrogen inside the containment is not clear. Research work analyzing hydrogen distribution and its concentration variation, in particular, is insufficient, involving failure in position variation.

This study analyzes hydrogen behavior in the containment building of an APR1400 nuclear plant during hydrogen release from different direction failure places. It also analyzes the distribution of gas mixtures of hydrogen, air, and steam at several positions in the containment. Afterward, the installation of PAR is examined.

2. Calculation grids and conditions

2.1. Geometry and grids

Fig. 1 shows the inner shape and Fig. 2 shows the calculation grids of the containment building of the APR1400 nuclear plant. The diameter and height are 22.86 m and 79.4 m, respectively. The lower part of the containment is composed of some compartments and pipe lines. The in-containment refueling water storage tank (IRWST) is placed on the bottom as annular shape, which depth is 3.5 m. The reactor vessel is located in the middle

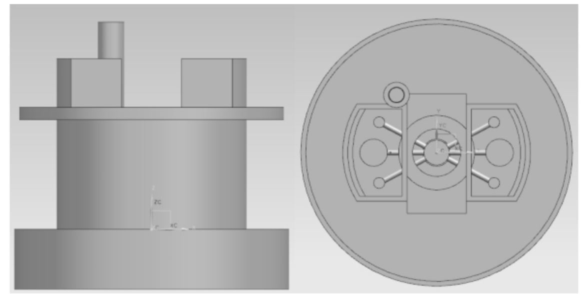

Fig. 1. Inner shape of the containment building of the APR1400 nuclear plant.

and two steam generators and cooler pumps are placed to be symmetrical. Compartment panels are located among the parts, and the parts are connected with pressurized tubes. The failure locations are assumed on the pressurized tube surface. The total number of grids is 2700,000 and the grids are generated using NX7.5 and ICEM–CFD codes. The grids are densely generated near the failure range to reduce error from high velocity and high pressure gradient.

2.2. Calculation conditions

The calculation code used in this study is ANSYS CFX. Transient term is discretized with second order backward Euler scheme. It is second-order accurate in time, and given by

$$\frac{\partial}{\partial t}\int_V \rho\Phi \mathrm{d}\boldsymbol{V} = \boldsymbol{V}\frac{1}{\Delta t}\left(\frac{3}{2}(\rho\Phi) - 2(\rho\Phi)^0 + \frac{1}{2}(\rho\Phi)^{00}\right)$$

where $()^0$ and $()^{00}$ are the old and one more step old time level solution values.

The k-omega based SST model is used on turbulent flow, which accounts for the transport of the turbulent shear stress and gives highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients. It solves two transport equations, one for the turbulent kinetic energy, k, and one for the turbulent frequency, ω. The equations are given as

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \beta'\rho k w + P_{kb}$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho U_j w)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_w}\right)\frac{\partial w}{\partial x_j}\right] + \alpha\frac{w}{k}P_k - \beta'\rho w^2 + P_{\omega b}$$

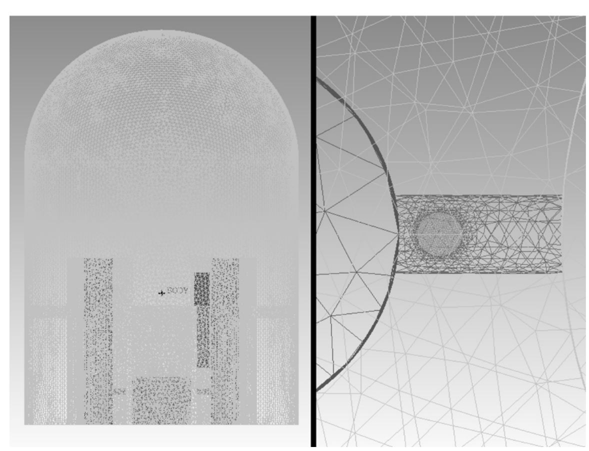

Fig. 2. Calculation grids and enlarged grids near failure position.