Development of a Tool for an Evaluation of PAR performance Characteristics in SMART

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1. Introduction

Among hydrogen mitigation devices, passive auto-catalytic recombiners (PAR) are commonly used in nuclear reactor containments because of its passive nature. In SMART (system integrated modular advanced reactor) a hydrogen mitigation system based on PAR is adopted.

In general, a PAR is composed of a small cassette or cartridge and a large open chamber. The cartridge of a PAR containing small plates coated with palladium or platinum is the main part of a PAR for hydrogen recombination with oxygen. The chamber containing the PAR cartridge works as a housing to protect the cartridge from environment and enhances a hydrogen removal rate of a PAR by chimney effect. So the combination of a PAR cartridge and a chamber of a PAR gives its characteristic of hydrogen depletion

During decades, many PAR manufacturers have appeared and produce many types of PARs. Because the characteristics of hydrogen depletion may different, it may be required to include the correlations of hydrogen removal rates of commercially available PARs in accident analysis codes to evaluate hydrogen safety in a nuclear power plant (NPP).

Each PAR may have relatively better points compared to other PARs. It is interesting to understand hydrogen removal characteristics of the PARs. In this study, only the hydrogen removal rates are compared without considering price, management efficiency, or negative effect such as an auto-ignition by PAR. In this study, PARs from 5 vendors, which are AREVA, AECL, NIS, KNT, CERACOM, are considered to evaluate hydrogen removal characteristics. And a software tool is developed to evaluate the PAR performance characteristics.

2. Methods and Results

2.1 Hydrogen Removal Rate of PARs

Even though the shapes of PAR chambers and cartridges are different, PAR performances of hydrogen depletion are integrated into correlations. The correlations are useful for a macroscopic analysis of hydrogen depletion in a compartment or containment.

Many PAR vendors have developed correlations from experimental data to represent their PAR performances. The followings show the correlations developed by the vendors.

$$R = \eta\, x_{\min}(A \times p_{bar} + B)\tanh(100 x_{\min,\lim}) \qquad (1)$$

Eq. (1) is a correlation for the AREVA PARs, where x_{h2} is a hydrogen volume fraction. AREVA PARs [1] have a different correlation comparing with the others, which shows there is no dependency on the temperature, only the pressure and the hydrogen concentration are needed to analyze the hydrogen removal rate. AREVA provides two groups of PARs dependent on their heights. The AREVA correlation is applicable to any sized PARs, but only recently-developed tall PARs (FR1-380T, FR1-750T and FR1-1500T) are considered in this study. Three different sizes are available (small, medium and large), each size has its own capability which can be represented in the catalytic plate number. Moreover, the coefficients A and B can also determine by referring to their values in each PAR's size.

$$R = 0.66 \times N \times (a_1 + a_2 \times x_{h2} + a_3 \times x_{h2}^2) \times \left(\frac{P}{T}\right) \qquad (2)$$

Eq. (2) is a correlation for the KNT PARs, where x_{h2} is a hydrogen volume fraction in percent. KNT [4] provides three kinds of PARs with difference sizes, which are KPAR-40, KPAR-80 and KPAR-160. The coefficient N in the correlation is a multiplication factor for larger PARs than KPAR-40. In this correlation the pressure, temperature and hydrogen concentration are considered as parameters to indicate the hydrogen removal rate.

$$R = S \times k \times (x_{h2} - 0.15)^{1.16} P\left(\frac{273}{T}\right) \qquad (3)$$

Eq. (3) is a correlation for the CERACOMB PARs, where x_{h2} is a hydrogen volume fraction in percent. CERACOMB [5] has almost the same mechanism of the previous PARs venders. It has three different sizes, each size has a certain number catalytic plates which are various among the PAR's chamber size. The correlation has a dependency on pressure, temperature and hydrogen concentration. Moreover, the k factor can be determined with respect to the PAR's size.

$$R = \eta 1.134 x_{h2}^{1.307} \frac{p}{R_u T} \qquad (4)$$

Eq. (4) is a correlation for the NIS PAR, where x_{h2} is a hydrogen volume fraction. In case of NIS [1], there is only one size available comparing with the previous companies. As shown in the above correlation, there is no changeable parameter depending on the PAR size. In other hand, the required parameters are pressure, temperature, hydrogen concentration and gas constant to perform the analysis of hydrogen removal. After comparing hydrogen removal rate with the other PARs, NIS is considered as a large size PAR.

$$R = k\left(0.15196x_{h2} + 0.0126x_{h2}^2\right)\left(\frac{298}{T}\right)^{1.10974}P^{0.57769} \quad (5)$$

Eq. (5) is a correlation for the AECL PAR, where x_{h2} is a hydrogen volume fraction in percent. AECL [1] provide only one model of PAR. As represented in the correlation, the same parameters which are required in the previous cases pressure, temperature and hydrogen concentration are necessary in their PAR. Parameter k is used in this correlation as a conversion factor between different units. After considering some design specification regarding the AECL PAR and comparing that with the other PARs, AECL is considered as a medium size PAR.

2.3 PAR Behavior Evaluation

2.3.1 Small Size PAR Evaluation

As shown in Fig. 1, the depletion rates among the small size PARs have been compared. The test conditions are pressure of 1.5 bar and temperature of 333 K, which mostly represent the severe accident condition to calculate the removal rate. In general the hydrogen depletion rates of the three PARs increase along the increasing of the hydrogen concentration but AREVA's small PAR, FR380T, gives the highest value of the removal rate.

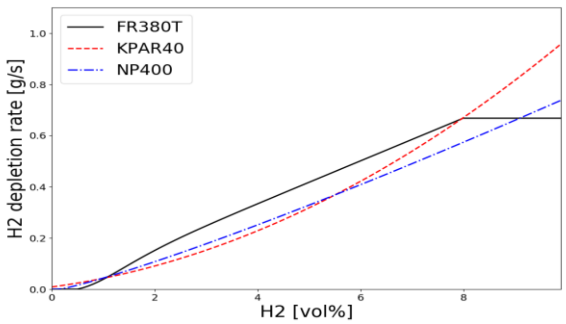

Fig. 1. Hydrogen Concentration Analysis of small PARs

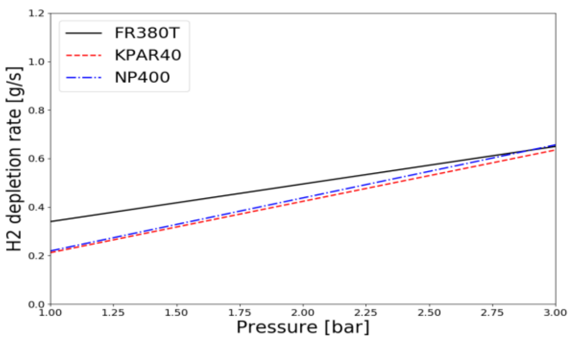

Fig. 2. Pressure Analysis of small PARs

A dependency of the hydrogen removal rates on pressure are evaluated for the three small PARs. Test conditions are hydrogen concentration of 5 vol% and temperature of 333 K. Fig. 2 shows a general tendency of the pressure dependency of the small PARs. But the CERACOM PAR gives the highest depletion rate compared with other PARs at an increased pressure.

2.3.2 Medium Size PAR Evaluation

In this part the AECL PAR is added. As shown in Fig. 3, along the test conditions used in this case, which are pressure of 1.5 bar and temperature of 333 K same as the previous small case, the most noticeable effect is that the removal rate has been increased due to the larger size than previous one. AREVA's FR750T and CERACOMB's NP800 are showing similar behavior in removing the released hydrogen. On other hand, the AECL PAR gives a lowest removal rate among the medium-size PARs.

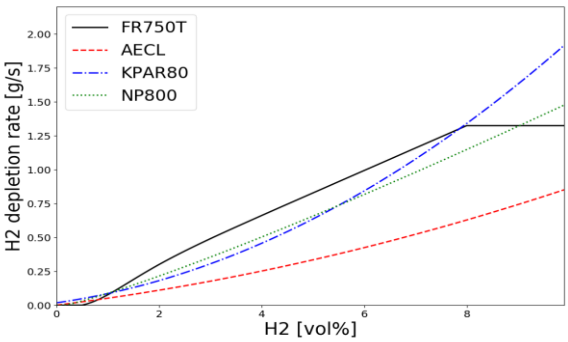

Fig.3. Hydrogen Concentration Analysis of mid. PARs.

In the pressure dependency case as shown in Fig. 4, the test conditions are 5% of the hydrogen concentration and temperature of 333 K. All the medium size PARs show increase of the depletion rates along the pressure increase similar to the small size PARs.

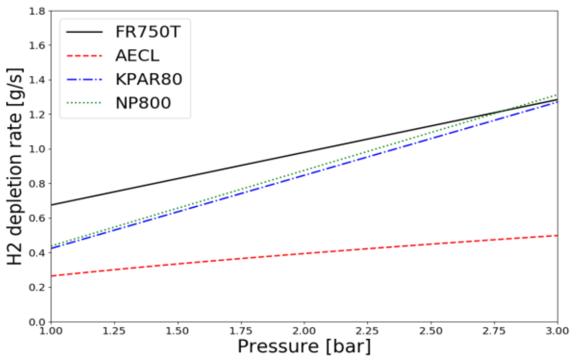

Fig. 4. Pressure Analysis of mid. PARs

Temperature dependency of the hydrogen depletion rates are depicted in Fig. 5. As shown in Fig. 5, most of the PARs except the AREVA PAR give decreased removal rates as temperature increases at the conditions of 5% hydrogen concentration and 1.5 bar pressure. The

AREVA PAR has a constant behavior due to the correlation independent on temperature. In a confined region like containment, a temperature increase directly affects a pressure increase. So the reduction of the removal rates from a temperature increase may be cancelled by its increment from a pressure increase. So, it is recommended to study the AREVA PAR's characteristic of the removal rate on the effect of a pressure rise by a temperature increase.

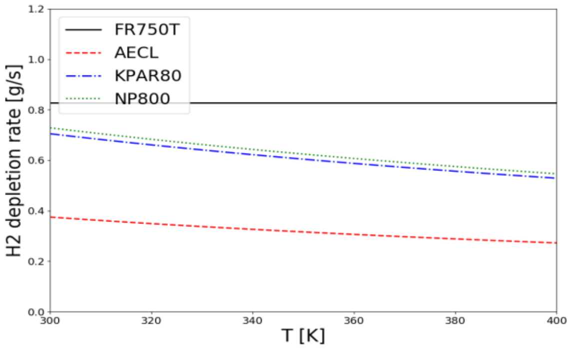

Fig. 5. Temperature Analysis of mid. PARs

2.3.3 Large Size Evaluation

In this case the characteristics of depletion rates of large PARs have been studied. Base on the size information of the NIS PAR, it is included in the group of large size PARs. The same test conditions as the previous cases have been used for removal rate dependency on a hydrogen concentration. The NIS and CERACOMB NP1600 are behaving very similarly.

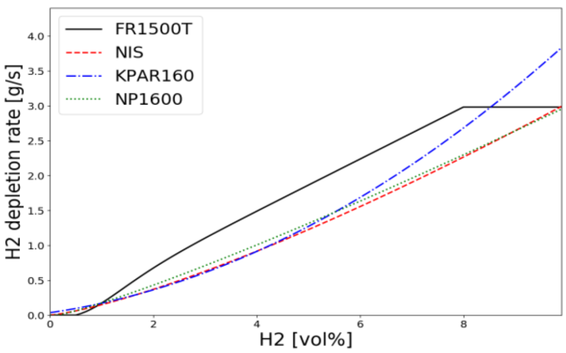

Fig. 6. Hydrogen Concentration Analysis of large PARs

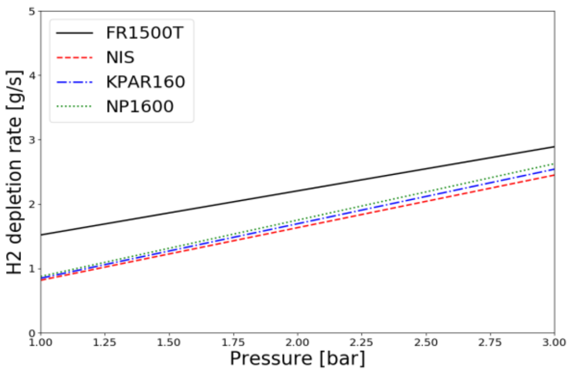

Fig. 7. Pressure Analysis of large PARs

The characteristics of the removal rates depending on pressure and temperature for the large size PARs are depicted in Figs. 7 and 8. Interestingly the behaviors of the removal rates on the pressure and temperature increases are very similar among the KNT KPAR160, NIS and CERACOMB NP1600 PARs.

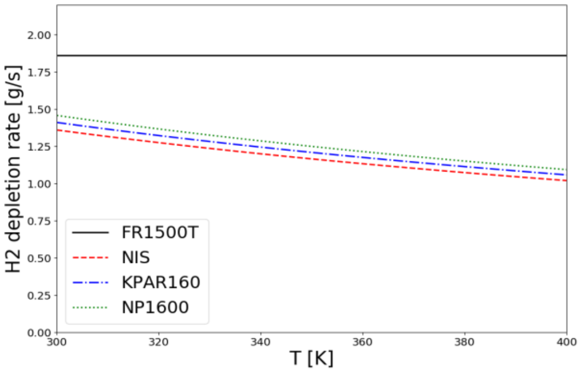

Fig. 8. Temperature Analysis of large PARs

2.4. Lumped Analysis of PAR Performance

In order to decide PAR configuration in a containment such as how many or where PARs be installed, an effort must be made. It is still believed that a PAR configuration is designed by engineer's judgment or experience based on characteristics of a hydrogen release and distribution of a nuclear reactor and containment. A hydrogen generation rate during a severe accident and a containment free volume are the most important information for decision of a PAR configuration. In this study, a python program has been developed to help the design of a PAR configuration.

2.4.1. Development of a lumped analysis tool

A single volume lumped analysis code has been developed to support design of a PAR configuration in a containment. The code includes 2 program modules, which are thermal properties of gas species and hydrogen removal rates of PARs. Equations for conservations of mass and energy of a gas mixture are solved every time step. Heat loss to a containment wall is modeled by assuming a natural convective heat transfer. Hydrogen mass released into containment is added in a mass source of the mass conservation equation. This single-volume lumped analysis code can give very accurate results in the case of homogeneous hydrogen distribution. But it may give approximate results when there is exist of a gradient in a distribution of hydrogen concentration.

2.4.2. Analysis of PAR performance in SMART

In order to introduce the applicability of the lumped analysis code, it was applied for design of a PAR configuration in a SMART upper containment area (UCA). The SMART UCA has a free volume of 52,628 m^3 and surface area of 11,379 m^2. Sixteen small-sized PARs (FR-380T) manufactured by AREVA are assumed to be installed in the SMART UCA. And hydrogen mass released into UCA was obtained from linear multiplication of the data from a MELCOR analysis of a station blackout accident in SMART to satisfy a condition of 100% oxidation of the SMART active core. The total hydrogen mass released into UCA in this calculation is about 193 kg. In this calculation it is assumed that heat transfer coefficient by a natural convection in UCA is 1 W/m^2-K.

Fig (9) shows the released hydrogen mass and inventory of the mass along time. During 50,000s, about 122 kg of hydrogen is removed by the PARs installed in UCA.

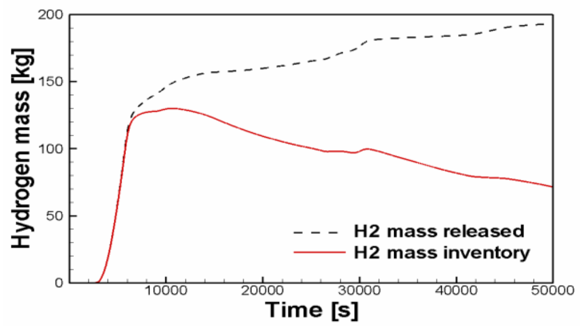

Fig. 9. Hydrogen mass in the SMART UCA

A volume-averaged concentration of hydrogen in UCA increases when the hydrogen is released into UCA. But recombination of the hydrogen by PARs installed in UCA reduces the hydrogen concentration continuously. The lumped analysis code developed in this study predicts that maximum concentration of hydrogen reaches 3.18 vol% which is below a flammability limit of hydrogen and air mixture which is about 4 vol%.

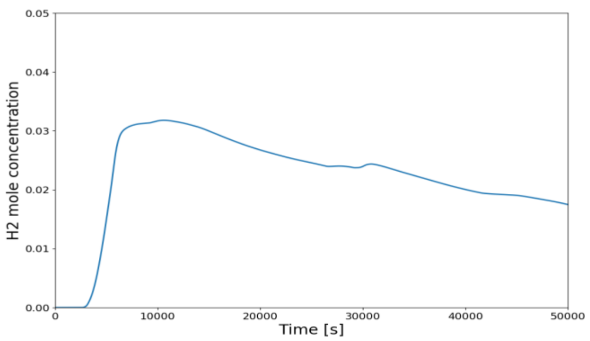

Fig. 10. Hydrogen concentration along time

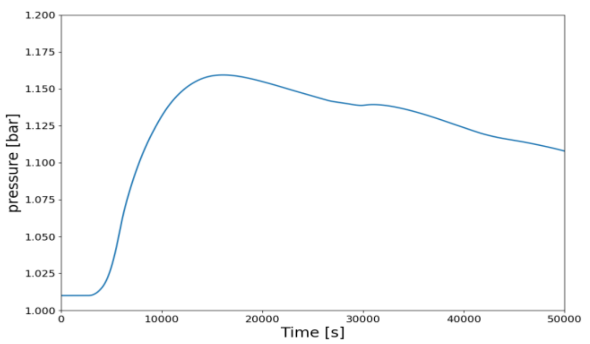

Fig. 11. Pressure of SMART UCA along time

Fig. 10 shows the UCA pressure in time. The pressure increases up to 1.16 bar by a heat released from the PAR activation. The pressure decreases after 15,000s because of a heat loss to concrete walls in the containment. If the heat loss to the containment walls is not considered, the containment pressure may increase up to an AICC pressure (adiabatic isochoric combustion), which is about 2.2 bar in the case of SMART.

3. Conclusions

The characteristics of PAR performance in hydrogen depletion have been studied. In order to evaluate the PAR performance characteristics, a python program has been developed. The equations to correlate a hydrogen removal rate with thermal properties of a hydrogen mixture gas developed by PAR vendors were implemented in the code. Dependencies of the hydrogen depletion rates on hydrogen concentration, pressure and temperature were clarified in this study. And the code was applied for a lumped analysis of hydrogen depletion by PARs installed in the SMART containment. The hydrogen depletion characteristic in the containment calculated by the lumped-parameter code will be evaluated by comparing with a result from a 3-D detail analysis

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