Theoretical Study on Sodium-Water Reaction in Printed Circuit Steam Generator

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1. Introduction

Prompt detection of steam-to-sodium leaks in the steam generator of a sodium-cooled fast reactor (SFR) is one of the most important economic and safety issues to be addressed in designing and operating an SFR. In the case of small or intermediate scale leaks, detecting of dissolved hydrogen in sodium and monitoring of cover gas pressure are carried out in real time. During the sodium-water reaction, therefore the hydrogen generation rate needs to be accurately predicted to design the leak detection system.

A large scale water/steam leak into the sodium channel produces an exothermic chemical reaction with sudden generation of a large amount of hydrogen gas. The pressure discontinuation by the abrupt pressure buildup owing to the high pressure hydrogen bubble results in propagation of the shock wave through the system. The pressure pulses thus produced can exert large forces on the structural members. Accordingly, the design of the steam generator system must consider the effects of potential sodium-water reactions to ensure structural integrity and to provide means for mitigating the pressure effects.

Recently, the printed circuit steam generator (PCSG) has been considered for the SFR application due to their high power density and good mechanical integrity. Particularly, the PCSG has a potential to significantly enhance the safety of the SFR by reducing the consequences of the sodium-water reaction [1,2].

This work focuses on the theoretical study on the sodium-water reaction in the PCSG. The hydrogen generation rate is calculated to find proper means to detect the small and intermediate leaks in PCSG. The initial pressure spike after large leak is evaluated theoretically to check the integrity of the PCSG system.

2. Calculation of Hydrogen Generation Rate

Fig. 1 shows a schematic model for obtaining the steam leak rate in PCSG. It was assumed that a steam injection device is connected to a sodium channel. In order to figure out the effect of the leak diameter at a leakage site, the steam leak rates were calculated changing the leak diameter. A critical flow was assumed due to the big difference between the steam and sodium sides. The steam leak rate through the steam injection channel can be calculated the following critical flow correlation [3]:

$$\dot{m}_{leak} = \frac{0.53 \times P_{tube} \times \frac{\pi}{4} d_{leak}^2}{1.62708 \times 10^{-7} \times (h_g - 430.195)} \quad (1)$$

In the equation (1), $\dot{m}_{leak}$ is the steam leak rate (g/s), P_{tube} the steam saturation pressure (Pa), d_{leak} the leak diameter (m), and h_g the steam enthalpy (kJ/kg). It was assumed that the leakage site is located at the center in a longitudinal direction of the sodium flow path. The temperature, pressure, and enthalpy of the steam were assumed to be 421℃, 16.8 MPa, and 3016 kJ/kg, respectively.

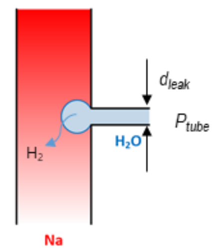

Fig. 1. Schematic model for calculating the steam leak rate.

The reaction equations governing a sodium-water reaction are as follows:

$$2Na + H_2O \rightarrow Na_2O + H_2 \qquad \beta \text{ (reaction frequency constant)}$$
$$Na + H_2O \rightarrow NaOH + 1/2H_2 \qquad 1-\beta$$
$$\overline{(1+\beta)Na + H_2O \rightarrow \beta Na_2O + (1-\beta)NaOH + 1/2(1+\beta)H_2}$$

It was assumed that sufficient amount of the sodium is supplied to completely react with all the leaked steam. Referring to the reference [4], the reaction frequency constant was determined to be 0.4. Accordingly, the hydrogen generation rate can be expressed as follows:

$$\dot{m}_{H_2} = 0.7 \frac{M_{H_2}}{M_{H_2O}} \dot{m}_{leak} , \quad (2)$$

where $\dot{m}_{H_2}$ is the hydrogen generation rate (g/s), M_{H_2} the molar mass of the hydrogen, and M_{H_2O} the molar mass of the steam.

The hydrogen concentration at the sodium exit of the PCSG can be obtained as:

$$C = \frac{\dot{m}_{H_2}}{\dot{m}_{sodium}} , \quad (3)$$

where C is the sodium concentration and $\dot{m}_{sodium}$ is the total sodium flow (g/s) in the PCSG. The total sodium flow in the PCSG was set to be 2795 g/s. The saturation concentration of the hydrogen in sodium is calculated as:

$$\log_{10} C_{sat} = 7.08 - 3380/T , \quad (4)$$

where C_{sat} is the hydrogen saturation concentration (ppm) and T is the sodium temperature (K). When the sodium temperature is assumed to be 332℃, the hydrogen saturation concentration is 31.23 ppm.

Using the equations (1)-(3), the steam leak rate, hydrogen generation rate, hydrogen concentration were calculated under various leak diameter conditions ranging 0.01 to 0.5 mm (Table I). As the leak diameter becomes 0.01 mm, the steam leak rate is about 2 mg/s and the increase in the hydrogen concentration reaches about 50 ppb, which is the detectable value when measured by a hydrogen meter. In the case of PGSFR SG, a steam leak of about 350 mg/s can increase the hydrogen concentration at the sodium exit by 50 ppb. The leak detection capability under a very small leak condition is dramatically increased in the PCSG because the sodium flow is much smaller than that in the shell-and-tube steam generator.

As the leak diameter reaches 0.26 mm (the steam leak rate = 1.12 g/s), the hydrogen concentration at the sodium exit of the PCSG becomes saturated and undissolved hydrogen is present in the sodium in a gaseous state. Gaseous hydrogen moves into the expansion tank, which results in increase in the pressure of the cover gas. The increase in the pressure is measured by pressure gauges in the expansion tank to detect the intermediate scale steam leak. In the case of PGSFR SG, a leak rate of about 170 g/s is required to produce the gaseous hydrogen in the sodium.

Table I: Hydrogen generation by steam leak in PCSG

Leakage diamete r (mm)	Steam leak rate (g/s)	Hydrogen generation rate (g/s)	Hydrogen concentration (ppm)
0.01	0.001652	0.0001294	0.0463
0.02	0.006609	0.0005176	0.185
0.05	0.04131	0.003235	1.157
0.26	1.117	0.08748	31.30
0.5	4.131	0.3235	115.7

2. Calculation of Pressure Spike using SWAAM-II

SWAAM-II (Sodium Water Advanced Analysis Method-II) code developed by ANL was used to analyze the initial pressure spike after the large scale steam leak accident in PCSG. Fig. 2 shows a single sodium channel modeling for PCSG analysis. It was assumed that the steam injection line is installed at the center of the sodium channel. The steam channel of the PCSG was not included in the modeling and the steam leak rate was set at the leak site as a boundary condition. The hydraulic diameters for the sodium channel, sodium header, and sodium piping were 4.2, 275.9, and 50.8 mm, respectively. Fig. 3 displays the nodalization for an arbitrary sodium-water reaction experimental loop. The loop consists of a PCSG, sodium piping, two rupture discs, an expansion tank, and a sodium dump tank. Six nodes (301~306) of equal length form the single sodium channel and a total length of the sodium channel in PCSG is 1 m. Two junctions (501, 507) at both ends of the sodium channel are connected to the sodium header nodes (300, 307). The lengths of the sodium headers and the sodium piping were set to be 0.5 and 1 m, respectively. The rupture discs burst as the magnitude of the pressure pulse exceeds 1 MPa.

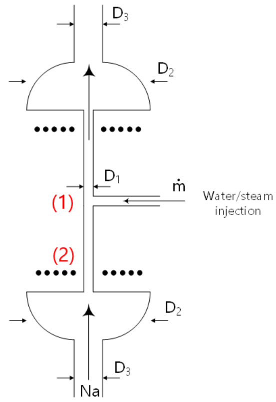

Fig. 2. Modeling of a single sodium channel in PCSG.

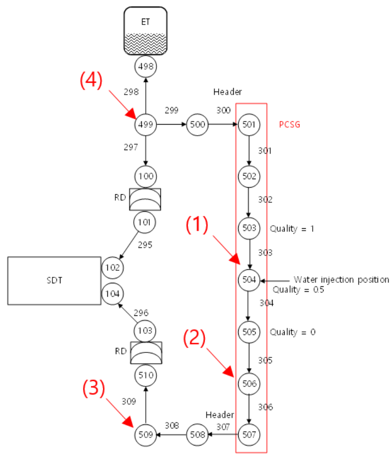

Fig. 3. Nodalization for SWAAM-II analysis.

Figs. 4-7 display the pressures at the major junctions (504, 506, 509, 499). Four kinds of leak rates including 0.0413, 0.165, 1.49, and 10.6 g/s were applied as the boundary conditions at the leakage site by changing the leak diameter from 50 to 800 ㎛. The junction 504 (position (1)) is the leakage site and a source of the pressure pulses. The peak pressure of the initial spike after the large leak increases as the leak rate increases (Fig. 4). The peak pressure goes up to about 18 MPa at the leak rate of 10.6 g/s. It was found that the abrupt pressure buildup easily occurred at leak rate as low as 10 g/s due to the small size effect of the PCSG flow channel. Actually, the hydraulic diameter of sodium channel in PCSG (~ 4 mm) is far smaller than that of the shell in shell-and-tube steam generator (1 m). The duration time of the pressure spike does not correlate with the leak rate and lasts for a very short time, less than 2 ms.

Fig. 5 shows the pressure trends at the junction 506 (position (2)). The pressure waves generated in the source of the PCSG become attenuated and fluctuated as they propagate to both ends of the sodium channel.

Fig. 6 represents the pressure fluctuations at the junction 509 (position (3)) which is located at the upstream of the rupture disc on the cold leg side. The very high pressure generated at the source dramatically decreases by the big area change in the sodium header. As the leak rate increases more than 1.49 g/s, the rupture disc burst and the pressure is stabilized under 1 MPa.

Fig. 7 shows the pressure fluctuations at the junction 499 (position (4)) which is located at the upstream of the rupture disc on the hot leg side. There is the expansion tank at the top of the hot leg. Thus the pressure weakens significantly as the pressure pulse reaches the cover gas of the expansion tank. Therefore, the pressures on the hot leg side are kept under 0.4 MPa and the rupture disc also did not burst.

In this study, the tubes of the intermediate heat exchanger were not taken into account for simplicity of the analysis. However, based on the above results, the integrity of the intermediate heat exchanger could be estimated to be sound because the magnitude of the pressure pulses decreases under 1 MPa as they travel further from the source.

3. Conclusions

Theoretical study on the sodium-water reaction in PCSG for SFR application was carried out. The hydrogen generation rates depending on the steam leak rate were estimated to provide the proper means for prompt detection of the small and intermediate scale leak in PCSG. The initial pressure spike was also analyzed in PCSG configuration with SWAAM-II code. Based on the results, the integrity of the PCSG system turned out to be maintained after the large leak accident.

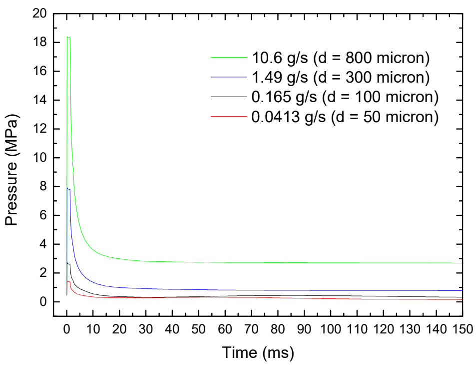

Fig. 4. Pressures at junction 504; position (1).

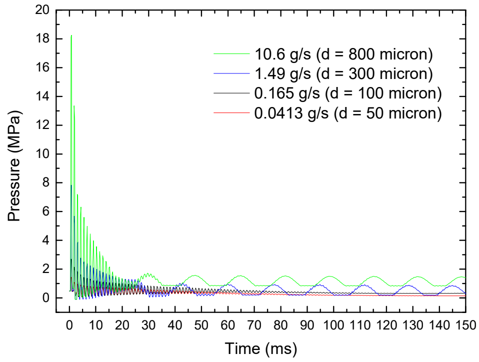

Fig. 5. Pressures at junction 506; position (2).

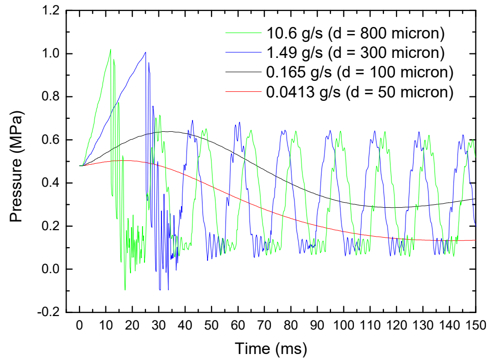

Fig. 6. Pressures at junction 509; position (3).

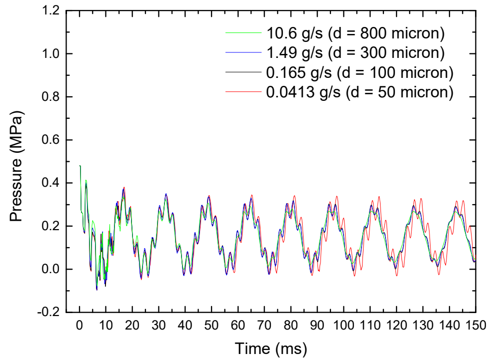

Fig. 7. Pressures at junction 499; position (4).

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