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Sodium-Water Reactions in Printed Circuit Steam Generator for SFR Application

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1. Introduction

Printed Circuit Heat exchanger (PCHE) has completely different features compared to a conventional shell-and-tube heat exchanger. Small flow channels of PCHE are fabricated on metallic plates by photochemical etching. The small channels increase the channel surface density dramatically. All the plates are assembled by diffusion bonding, which results in great strength of bonding layer. Owing to the high power density of PCHE, it has been used as single-phase gas heat exchangers because heat transfer efficiency of gas is not good. Lately, attempts have been made to utilize PCHE as a steam generator (Printed Circuit Steam Generator; PCSG) in nuclear power plants. For example, it was reported that by employing PCSG in SMR IRIS, 1/43 volume reduction of the component was achieved.

Recently, the PCSG has been considered for the SFR application owing to their high power density and good mechanical integrity (Fig. 1). Particularly, the PCSG has a potential to significantly enhance the safety of the SFR by reducing the consequences of the sodium-water reaction [1-3].

In this work, the scenarios and consequences of the sodium-water reaction (SWR) in PCSG are predicted analytically based on the knowledge on the SWR in the conventional SG for the first time. Wastage rates, wastage depths, pressure buildup are quantitatively calculated with changing the steam leak rate in PCSG. Two different reference PCSGs being developed in KAERI, which include the prototype and scaled model of PCSG, are analyzed for this work. Finally, the inherent safety of PCSG to the SWR is discussed based on the calculated results.

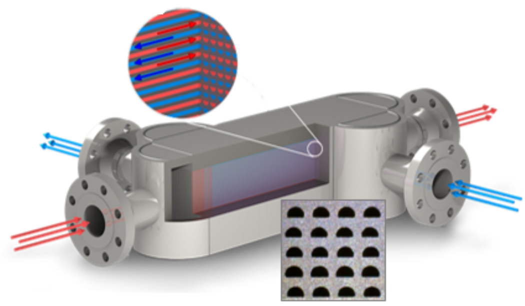


Fig. 1 Conceptual drawing of PCSG

2. Sodium-Water Reactions in Conventional SG

In steam generators for SFR, the sodium and water/steam are separated by the heat transfer tubes. If holes or breakage occurs in the tubes, the high pressure steam leaks into the sodium side, which leads to a SWR. In this section, the characteristics of the SWR in the convention SG are reviewed by reference to Hori's paper [4].

2.1 Wastage by small leak

When a small amount of water/steam flows into the sodium through the pinhole in the tube, normally, the leaking water is in the form of a jet stream which reacts with the sodium rapidly and violently and generates high temperature corrosive reaction products. Impingement of these product particles on adjacent tubes causes a combined corrosion/erosion effect on the tube surfaces, which is called wastage. Hori discussed the effects of various parameters on wastage based on the world's experimental data as follows [4].

Many experimental data have shown that the wastage rate increases with the water/steam leak rate and reaches a maximum at a certain leak rate. This critical leak rate varies according to the distance to the target. The effect of the target distance on the wastage rate can be well explained by the term L/D, where L is the distance between leak hole and target, and D is the leak hole diameter. At $L/D > 160$, no wastage practically happens because the jet does not reach the target. At the range of $25 < L/D < 160$, the wastage rate increases as L/D decreases, and reaches the maximum rate around $L/D = 25$. In this regime, a pitting pattern is observed on the target surface. At $L/D < 25$, the shape of the jet stream is distorted due to a short target distance and the wastage creates a toroidal pattern on the target surface. The wastage rate of the toroidal regime decreases with L/D.

Hori derived the following wastage rate correlation for Cr-Mo steel ($25 < L/D < 150$) from world-wide wastage data [4].

$$W_R = \frac{4000}{L}\exp\left\{-\left[0.1\left(\ln\frac{G}{24}\right)^2 + \frac{5500}{T_{Na}}\right]\right\}, \quad (1)$$

where W_R is the wastage rate (mm/s), G is the leak rate (g/s) and T_{Na} is the sodium temperature (K).

2.2 Large leak

According to Hori's paper [4], the results of large leak tests so far conducted at various organizations indicate that, except for some special configurations, the damage would be small, for example a slight wastage or bowing of surrounding tubes, and that no secondary failures would occur. The wastage effect is not as severe as in the case of the small-leak reaction because the reaction front moves with the sodium mass which is pushed away from the reaction point due to the large amount of hydrogen gas generated.

If a columnar bubble growth model (one-dimensional compressible liquid channel) is employed for predicting of the moving reaction front, the velocity of the gas-liquid interface and the initial pressure spike can be expressed as follows (Fig. 2).

$$u_L = \frac{P_B - P_O}{\rho_L c} \quad (2)$$

$$P_B = \frac{1}{2} P_O \left(1 + \sqrt{1 + \frac{4\rho_L c R T \dot{m}}{2AP_O^2}}\right) \quad (3)$$

where u_L is the velocity of the gas-liquid interface, P_B is the pressure of gas, P_O is the pressure liquid, ρ_L is the density of sodium, c is the sonic velocity, R is the gas constant, T is the absolute temperature of gas, A is the cross-sectional area of channel, and $\dot{m}$ is the hydrogen generation rate.

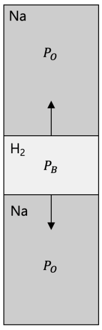


Fig. 2 One-dimensional columnar bubbler growth model

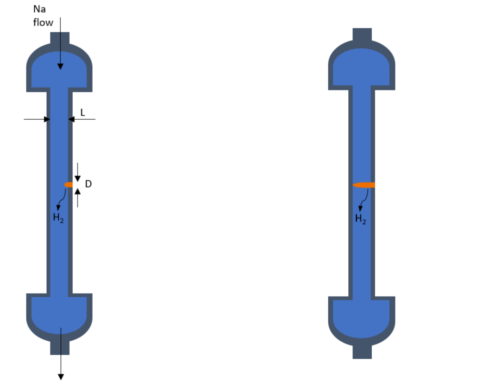
3. Sodium-Water Reactions in PCSG

3.1 Scenarios of Leak Accidents in PCSG

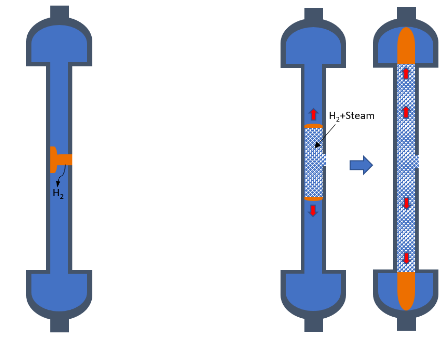
In the PCSGs, *L* is fixed by the channel geometry (Fig. 3a). Steam leak rate is determined by the leak diameter because steam pressure is assumed to be constant. As the leak diameter increases, the leak rate increases but *L*/*D* decreases. If the same wastage phenomena mentioned in the section 2.1 are assumed to happen in a PCSG, the wastage can be divided into three regimes, including micro-leak regime (*L*/*D* > 160), pitting regime (25 < *L*/*D* < 160), toroidal regime (*L*/*D* < 25) (Fig. 3a-c). Moreover, the movement of the reaction interface by explosive hydrogen generation is expected to occur more easily due to the small cross-sectional area of channel and the small sodium flow rate per channel (Fig. 3d). It is assumed that if the hydrogen concentration in sodium at the leakage site ($C_{chanl}^{H_2}$) exceeds the saturation concentration ($C_{sat}^{H_2}$) at the sodium temperature, the gas bubble begins to grow.

3.2 Calculation of Wastage Rate in PCSG

Table I shows major parameters of the prototype and scaled model of PCSGs which are being developed in KAERI. The thermal power of the prototype is much larger than that of the scaled model. Dimensions of the sodium channel in the two heat exchangers are identical except for their length. The sodium flow rate per channel in the prototype is almost four times bigger than that of the scaled model.



(a) Micro-leak, *L*/*D* > 160 (b) Pitting regime, 25 < *L*/*D* < 160



(c) Toroidal regime, *L*/*D* < 25 (d) Movement of reaction interfaces, $C_{chanl}^{H_2} > C_{sat}^{H_2}$

Fig 3. Scenarios of leak accidents in PCSG

Table I: Prototype and scaled model of PCSG

	Prototype	Scaled model
Thermal power (MW)	24.5	0.7
Total sodium flow rate (kg/s)	97.8	2.8
Sodium flow rate per channel (g/s)	22.5	5.3
Sodium channel depth/width/length (mm)	4/4.5/2000	4/4.5/1000
Sodium inlet/outlet temperature (°C)	528/332	528/332
Steam pressure (MPa)	16.7	16.7

The wastage rates in the above two PCSGs were analytically calculated under various leak rate conditions ranging 0.001 – 10 g/s. The same analytical equations used in our previous work [3] were employed for predicting the steam leak rate, hydrogen generation rate, hydrogen concentration in sodium, and saturation hydrogen concentration. It was assumed that the leaking steam completely reacts with surrounding sodium to produce reaction products such as H_2, NaOH, etc. Sodium temperature of 480°C at the leakage site was taken as a conservative value of 50°C higher than the average temperature of the total sodium in the channel.

Under the sodium temperature condition, the saturation hydrogen concentration in sodium was estimated to be 391 ppm. The reaction interface movement by generation of gaseous hydrogen was assumed to start after the hydrogen concentration inside the channel reached 500 ppm. The velocity of the reaction interface was calculated using Eqs. (2) and (3) based on the columnar bubble growth model.

Detection of SWR was conducted by a hydrogen meter at the sodium exit of PCSG. SWR was assumed to be completely stopped 130 seconds after the hydrogen concentration at the sodium exit of PCSG reached 50 ppb. The delay time of 130 seconds was chosen by adding detection time of 30 seconds in hydrogen meter and steam drain and isolation time of 100 seconds.

The wastage rate was calculated using Eq. (1) in the pitting regime, $25 < L/D < 160$. The maximum wastage rate was assumed to be acquired at $L/D = 25$.

Fig. 4 represents a comprehensive analysis for the wastage phenomena in PCSGs. While the hydrogen concentration at the sodium exit of the scaled model reached 50 ppb at the steam leak rate of about 0.002 g/s, in the case of the prototype that happened at steam leak rate of about 0.06 g/s. The hydrogen concentration inside the channel in the scaled model reached 500 ppm at about 0.035 g/s, but in the prototype it occurred at about 0.15 g/s. The hydrogen concentrations at the sodium exit and channel inside are inversely proportional to the total sodium flow rate and sodium flow rate per channel, respectively. Accordingly, in the prototype both detection of SWR and movement of reaction front started at higher leak rates compared to the scaled model.

The wastage rate for the pitting regime was acquired at the steam leak rate ranging 0.01 – 0.4 g/s. As the leak rate increased, the wastage rate increased from 0.0017 to 0.13 mm/s. After the leak rate became higher than about 0.4 g/s, the wastage rate was assumed to decrease due to the change of the wastage regime. In Fig. 4, the wastage rate curve for the toroidal regime was arbitrarily drawn for the sake of understanding the wastage trend.

Although the wastage rates were obtained in a wide range of the leak rates, the maximum wastage rate turned out not to be practically achievable due to the pressure buildup by generation of hydrogen gas. For example, the pressure spike and the velocity of the reaction interface were estimated to be about 0.9 MPa and 0.6 m/s, respectively, when the reaction interface began to move along the channel in the scaled model at the leak rate of 0.035 g/s. As soon as the reaction interfaces move away from the leakage site, the wastage is believed to be stopped. The more leak rates occur, the faster sodium is pushed away, which leads to the rapid interruption of wastage. In the case of the prototype, the reaction interfaces started to move away at the leak rate of about 0.15 g/s.

Based on the above analysis of wastages in PCSGs, the wastage depths depending on the leak rates were estimated on both the prototype and scaled model (Fig. 5). It was assumed that if L/D is larger than 160, the steam jet does not affect the target wall. In the scaled model, the SWR can be detected by the hydrogen meter at the sodium exit during the pitting wastage. The wastage lasted for 130 seconds and the pitting depths were predicted to be 0.2 – 1.2 mm at the leak rates ranging 0.01 – 0.035 g/s.

In the case of the prototype, the SWR cannot be perceived at the leak rates ranging 0.01 – 0.06 g/s due to the undetectable hydrogen concentration of less than 50 ppb. This undetectable wastage was assumed to last for 30 minutes, and the wastage depths were calculated to be 2.98 – 35.8 mm. As the leak rate increased to more than 0.06 g/s, the wastage became detectable and the wastage depths were reduced to 3.43 – 7.35 mm owing to short reaction duration.

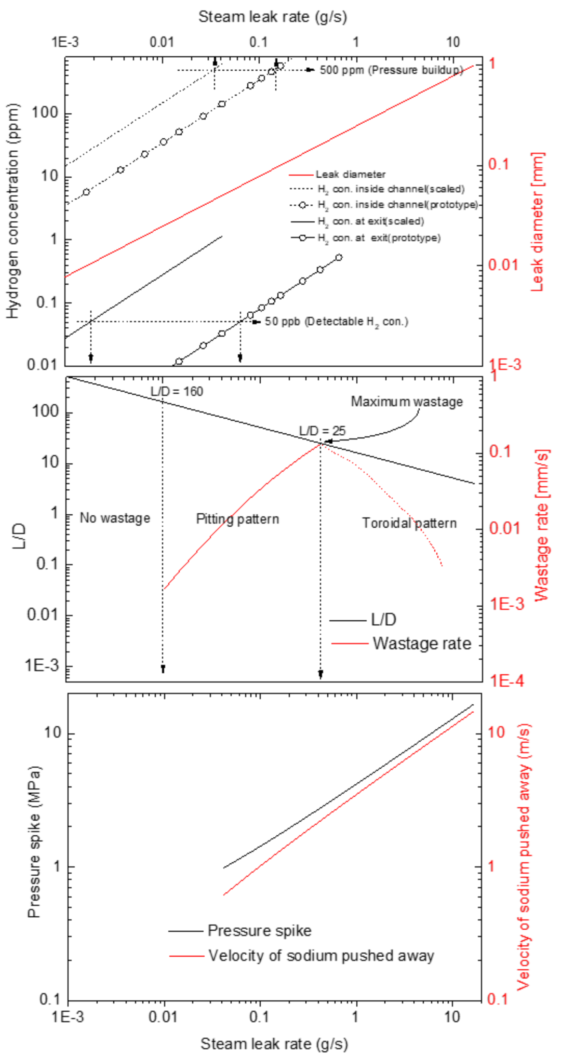


Fig 4. Analysis for wastages in PCSGs

4. Discussions on Inherent Safety of PCSG against SWR

The PCSG has many good features in terms of inherent safety against SWR compared to the conventional shell-and-tube steam generator. When the steam leak occurs and target wastage is initiated, damages are limited to inside a single narrow channel since the target distance (L) is fixed by the channel dimension and multiple channel effects do not exist. As the leak rate increases, the SWR could be easily detected because the hydrogen concentration rapidly rises up owing to the small flow rate in a small modular PCSG. Also, at the fixed L, the wastage would change from the pitting regime to the toroidal regime, which results in reduction of the wastage rate. Moreover, the wastage would be hampered by fast movement of the reaction front at a higher leak rate due to the small cross-sectional area of the channel. At a certain range of the leak rates, the target wall of a few millimeter thickness would be damaged enough to be penetrated (Fig. 5). However, the penetration of the channel wall would most likely cause another leakage hole in an adjacent steam channel. Then the leak rate would increase a lot, and the wastage would stop soon.

In case of the large leak in PCSGs, even if the leakage diameter is large enough to affect several sodium channels, no severe target wastage would occur in each channel and the situation would be terminated without significant damage by the movement of the reaction interface and burst of the rupture disc. Additionally, the larger diameter of the leak hole, the more slit-like it looks because of the narrow and long shape of channels. A previous study showed that the slit-like hole produced less wastage rate at the same leak rate than a circular hole [4].

It is worth discussing that the moving reaction interfaces would stop at the ends on the channels and make wastage jets to attack the header walls because they contact with plentiful sodium in headers (Fig. 3d). Unlike the channel wall, the header wall is thick enough (~ a few cm) to endure the wastage jet for a long time. Actually, the wastage rate in the header was estimated to be about 0.01 mm/s even if a leak rate of 100 g/s was assumed.

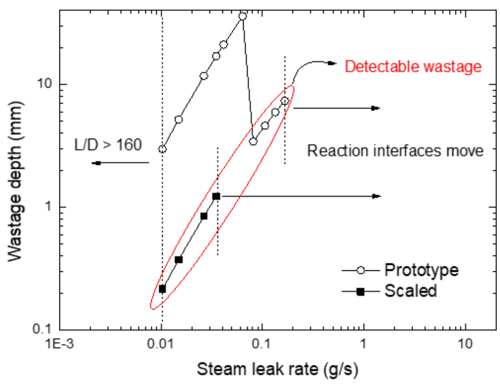


Fig 5. Predicted wastage depth in PCSGs

4. Conclusions

The scenarios and consequences of SWR in PCSG have been predicted analytically based on the knowledge on the SWR in the conventional SG. Wastage rates, wastage depths, pressure buildup were quantitatively calculated with changing the steam leak rate in PCSG. The unique channel geometry of PCSG caused the inherent safety features against the SWR, which suggests that PCSG would be a promising candidate to displace the conventional shell-and-tube steam generator.

This work has the limitation of carrying out only theoretical analysis with several assumptions. As a future work, therefore, the experiments to observe SWR in PCSGs will be conducted to validate the analytical results.

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