Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

Preliminary Study of Sodium-Water Reaction in the PCSG

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1. Introduction

A Sodium-cooled fast reactor (SFR) is liquid metal reactor using sodium as coolant. Typically water and sodium are used in steam generator of SFR to transfer heat from sodium to water. This kind of steam generator has a natural born risk. That is sodium-water reaction (SWR). If boundary between sodium and water, in case of steam generator tubes, is failed by any reason, sodium and water will contact then chemical reaction will be taken place according to the following chemical formula [1].

$$Na + H_2O \rightarrow NaOH + 1/2H_2 - 147.37 \text{ kJ/mol}$$

If sodium-water reaction is happened, pressure and temperature in steam generator are increased because this is highly exothermic reaction. And steam generator integrity is degraded by reaction product, NaOH, due to its corrosive property. In addition, hydrogen is generated by this reaction. The steam generator integrity is severely threatened by the hydrogen if venting of steam generator can't be implemented. Consequences of sodium-water reaction such as increase in steam generator temperature and pressure, and hydrogen explosion have always been safety issues of SFR. This safety issue is inevitable unless water is excluded like as Brayton cycle. Many researches [2~11] for prevention, detection, and mitigation of sodium-water reaction have been performed to solve this inherent risk.

However, these researches are related to not printed circuit steam generator (PCSG) but shell and type steam generator. Reason of necessity of SWR research for the PCSG is that the PCSG is being considered to apply to the PGSFR (Prototype Generation IV Sodium-cooled Fast Reactor), and there are no data and models for SWR in the PCSG up to now.

The PCSG is a kind of PCHE (Printed Circuit Heat Exchanger). The PCHE is manufactured by using diffusion bonding between chemically etched steel plates. Etching channel on steel board is shown in Figure 1. Schematic and cross-section of the PCHE are shown in Figure 2 [12].

In this study, water-air two-phase flow loop is manufactured for preliminary study of the SWR in the PCSG. In this case, chemical reaction is excluded and flow patterns under the PCSG operating condition are identified. Effect of chemical reaction will be considered in the further study.

Figure 1. PCHE platelet configuration

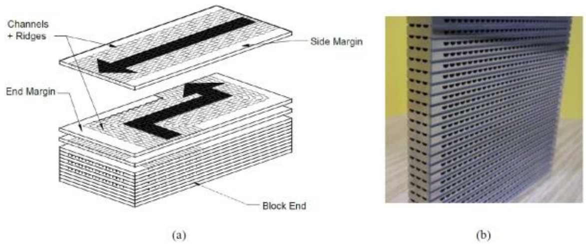


Figure 2. (a) plate stacking for bonding, (b) bonded printed circuit core

2. Experiment

The PCSG is expected to have strong points against SWR accident comparing with shell and tube type steam generator. These advantages are as follows.

- Reduced impingement wastage due to very short target distance
- Exclusion of damage propagation by wastage
- Effective accident management by modularization of the PCSG
- Low background noise caused by laminarization of SG flow due to small size tubes can facilitate acoustic detection of SWR.

Above advantages must be verified experimentally for applying the PCSG to the PGSFR. Therefore SWR experiment in the PCSG is planning now to demonstrate the above strong points. Two-phase (sodium and steam) flow pattern in failed tube may play a dominant role for wastage phenomenon. So experimental apparatus is made to find out what flow pattern is formed under the same PCSG operating flow as a preliminary study. Purposes of this fundamental test are visualization of two-phase flow pattern when one phase flows downward in tube and other phase is injected side of the tube. This test is helpful in doing SWR experiment and obtaining insight with the SWR in small tube because SWR can't be visualized and sodium is opaque.

2.1 Methodology

First of all, two-phase (water-air) flow pattern is measured to find out what kind of flow patterns exists in circumstance of cross flow within small tube. In SWR situation of the PCSG, flow direction of each phase is neither co-current nor counter-current flow. It's cross flow, but cross-section area is very small (I.D. = 4 mm). In this case, there are no research results of two-phase flow pattern. So, it is necessary to identify the flow patterns under the various flow conditions.

Secondly, sodium-water two phase flow pattern in the PCSG under operating condition will be estimated by similarity analysis based on the results of the water-air cross flow experiment. Effect of chemical reaction is excluded in this similarity analysis. Consideration of chemical reaction effect will be treated in further work.

2.2 Experimental apparatus and conditions

Experimental apparatus for flow visualization is designed as Figure 3 and made as shown in Figure 4. Water side of this apparatus is composed of water tank, pump, pressure and temperature measuring instruments, pipe, and test section. And air side of this consists of compressor, pressure regulator, flow meter, pipe, and test section connector.

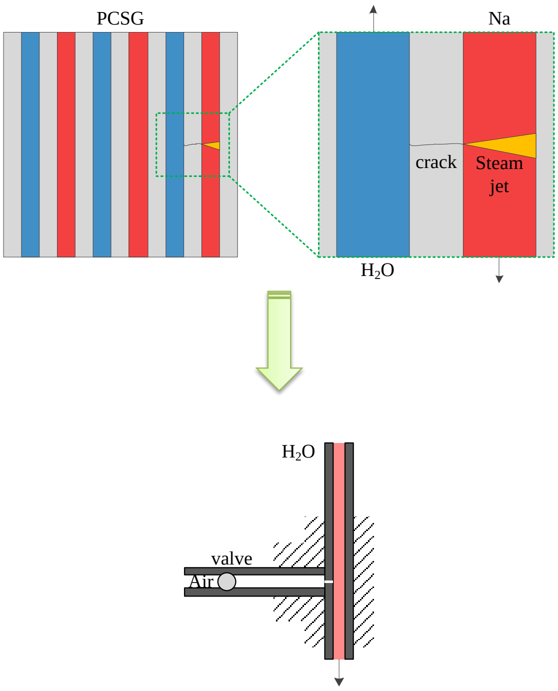


Figure 3. Test section design

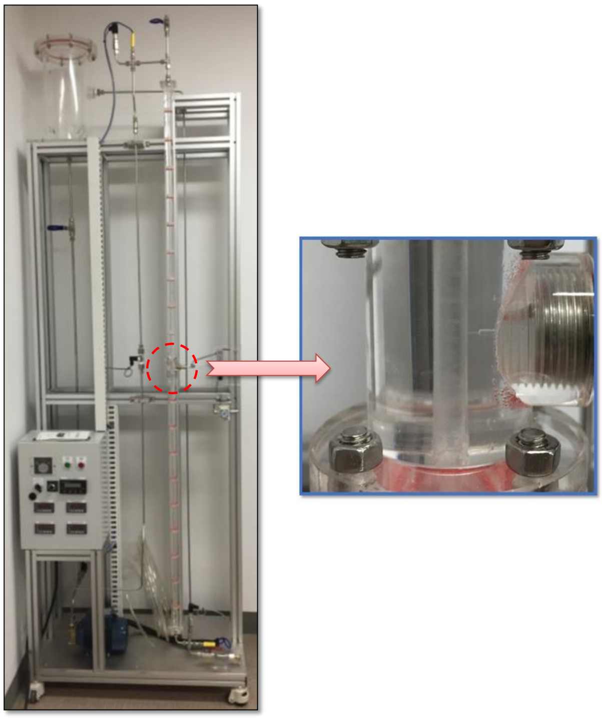


Figure 4. Experimental apparatus

Flow patterns are identified under conditions written in table 1. Designed sodium flow in the PCSG is 2.13 LPM. But various flow patterns can't appear in this water flow. So, lower flow (1.5, 1.0 LPM) is also used.

Table 1. Experimental Condition

Hole size (mm)	Test No.	Water Flow (LPM)	Air Pressure (bar)
2.0	2.0-A1	2.13	0.0
	2.0-A2		1.0
	2.0-A3		1.5
	2.0-A4		2.0
	2.0-A5		2.3
	2.0-A6		2.5
	2.0-A7		3.0
	2.0-A8		3.4
	2.0-B1	1.5	0.0
	2.0-B2		1.0
	2.0-B3		1.2
	2.0-B4		1.5
	2.0-B5		2.0
	2.0-C1	1.0	0.0
	2.0-C2		0.5
	2.0-C3		0.75
	2.0-C4		0.9
	2.0-C5		1.0
0.3	0.3-A1	2.13	0.0
	0.3-A2		1.0
	0.3-A3		2.0
	0.3-A4		3.0
	0.3-A5		4.0
	0.3-A6		5.0
	0.3-A7		6.0
	0.3-B1	1.5	0.0
	0.3-B2		1.0

	0.3-B3		2.0
	0.3-B4		3.0
	0.3-B5		4.0
	0.3-B6		5.0
	0.3-B7		6.0
	0.3-C1		0.0
	0.3-C2		0.8
	0.3-C3		1.2
	0.3-C4	1.0	1.4
	0.3-C5		2.0
	0.3-C6		2.4
	0.3-C7		2.6

3. Results and Conclusion

3.1 Identification of flow pattern

As a result of the experiment, it is identified that there are three flow patterns in situation of which air is injected into the side of downward flowing water tube. This result is represented in Figure 5. In this study, first pattern (green box) names 'Pattern I' that injecting air is entrained by downward water flow without contact with opposite tube wall. Flow pattern of downstream of injecting hole is identified as bubbly flow. Second one (orange box) names 'Pattern II'. It is flow that injecting air hit the opposite tube wall and interface between water and air is formed somewhere in upstream of air injecting hole. Flow pattern of downstream of the hole is observed as churn and annular flow. Third one (blue box) is characterized by void fraction of 1.0 and names 'Pattern III'. Water in tube is totally expelled both ends of tube by injecting air.

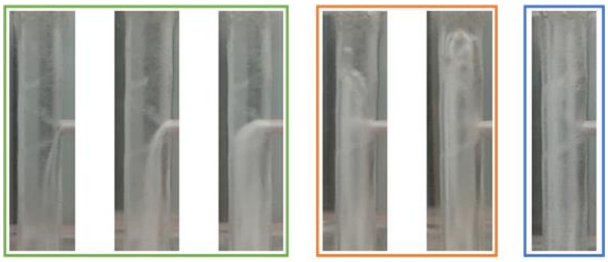
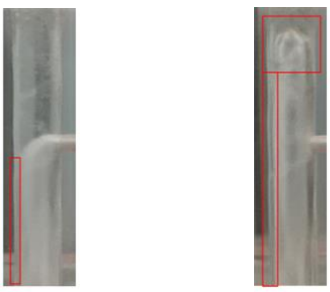


Figure 5. Flow patterns in situation of SWR in the PCSG



(a) Pattern I (b) Pattern II

Figure 6. Anticipated location of wastage

Among these patterns, it is predicted that the most severe wastage is happened in Pattern II. In case of Pattern I, wastage occurs in red box region shown in Figure 6 (a). If leaking steam into sodium side is continued, additional tube rupture can be taken place in the region. It is expected that amount of wastage exerted to tube wall is small in downstream of injecting hole because flow pattern in that space is bubbly flow.

However, Pattern II has larger interface area than Pattern I (Figure 6 (b)). It means wastage can take place in larger area than other flow pattern. Especially, interface between water and air in upstream of injection hole continuously exists during air injection. It means that possibility of wastage in that space is higher than other space. And it is observed that flow pattern of downstream of injection hole is churn or annular flow. In case of annular flow, SWR can occur near the tube wall. It implies that chemical reaction product can corrode the tube wall. Ultimately, additional tube failure can be happened by wastage. However, amount of wastage is much smaller than expected one if flow velocity is very fast and NaOH can't contact with the tube wall.

Pattern III is not important in point of wastage. This is because there is no interface between water and air in whole tube. In case of Pattern III, SWR will occur in header of the PCSG that located both upper and bottom end of tube. If the SWR only occurs in header, it is expected there is no damage propagation by wastage (multiple tube failure). In conclusion, Pattern II is a limiting flow pattern in point of wastage.

3.2 Flow regime map

Flow regime map is obtained by performing experiments in condition of Table 1 for 0.3 mm of hole size. Objective of making this map is estimation of what flow pattern is formed in the SWR experiment by similarity analysis. The reason of selecting experimental condition for 0.3 mm is that the SWR experiment will be carried out by using 0.3 mm hole size test section. Water-air two phase flow regime map for cross flow in small tube is shown as Figure 7.

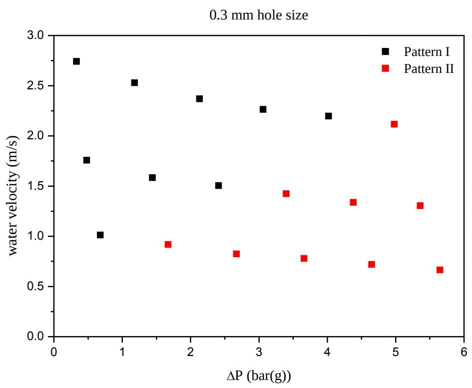


Figure 7. Flow regime map about preliminary test

Typically axes of two phase flow regime map consist of one phase velocity and other phase velocity. But x-axis label of Figure 7 is pressure difference because it can't be expressed by air velocity. Air velocity which is perpendicular to water flow direction can be calculated from measured flow rate. But air velocity which is parallel to water flow direction can't be calculated and measured. Air velocity is a function of pressure difference. So pressure difference between air side and water side is used substituting for air velocity.

Similarity analysis is also performed. In this similarity analysis, SWR experiment is original system and water-air experiment is model. This analysis is carried out to estimate anticipated flow pattern of SWR experiment under the operating condition based on above flow regime map (Figure 7). Theoretically Re, Fr, Eu, We, and Ma between original system and model are coincided for dynamic similarity. If it is impossible to square all dimensionless numbers, some numbers should be selected according to interesting physical phenomena. In this analysis, Re and We are selected for the similarity analysis. As a result of this analysis, required water and air velocity to obtain same sodium-water flow pattern under the operating condition are 7.6496 m/s and 9.5401 m/s, respectively. Calculated air velocity can convert flow rate (LPM) and result of similarity analysis is as Figure 8.

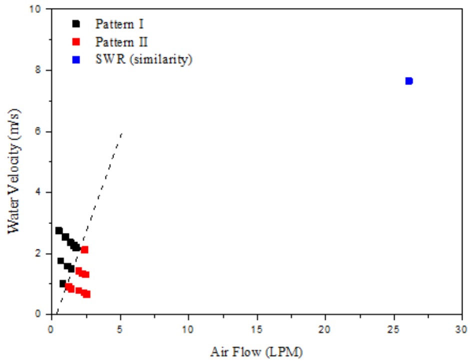


Figure 8. Result of similarity analysis

4. Conclusion

In this study, water-air experiment is performed for preliminary study of the SWR in the PCSG. In this preliminary experiment, flow patterns are identified in situation of which air flow is injected into the downward water flow. As results of the experiment, it is identified that the most severe wastage can occur in Pattern II. And it is predicted Pattern III occurs in the SWR experiment based on Figure 8. It noted that this result not considers effect of chemical reaction. It means Pattern III can be happened in the SWR experiment in the PCSG if chemical reaction is considered. Therefore it implies that the wastage is not taken place within failed tube.

It can be deduced that acoustic detector should be mounted on headers part of the PCSG and wastage in headers is considered when the SWR experiment in the PCSG is carried out.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP).
(No.2017M2A8A4018812 and No.2017M2A8A4018812)

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