Safety Issues of Sodium-Water Reaction in Gen-IV SFR

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1. Introduction

A Sodium-cooled fast reactor (SFR) is liquid metal reactor using sodium as coolant. SFRs can be classified two types of reactor that is pool type and loop type. Typically both type of SFR use sodium and water in steam generator to transfer heat from sodium to water. This kind of steam generator has a natural born risk. That is sodium-water reaction. 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 occurred according to the following formula.

$Na + H_2O \rightarrow NaOH + 1/2H_2 + 180$ kJ/mol

If sodium-water reaction is occurred, pressure and temperature in steam generator are increased because this is highly exothermic reaction. And also steam generator integrity is degraded by reaction product 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 in steam generator can't be performed. Consequences of sodium-water reaction such as increase in steam generator temperature and pressure, and hydrogen explosion were always safety issues of SFR. This safety issue can't be inevitable unless water is excluded like as Brayton cycle. Many researches [1~10] for prevention, detection, and mitigation of sodium-water reaction have been performed to solve this inherent risk.

However, these researches are not for printed circuit steam generator (PCSG) that is being considered to apply to the PGSFR but for shell and tube type steam generator. There are no data and models for sodium-water reaction in the PCSG. Studies for sodium-water reaction in the PCSG are necessary to safely apply PCSG to the PGSFR.

The PCSG is a kind of PCHE (Printed Circuit Heat Exchanger). The PCSG is composed multiple printed layer. Printed layer means etching channel on steel board like as Figure 1. Effectiveness, mechanical integrity, transient characteristics, and codification considerations have been already studied in this kind of heat exchangers [11].

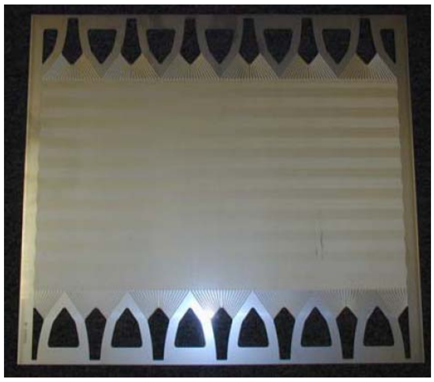

Figure 1. PCHE platelet configuration

In this study, researches for sodium-water reaction in shell and tube type steam generator are reviewed and sodium-water reaction in PCSG is discussed. Sodium-water reaction in PCSG is clarified and research plan is established through this study.

2. Review of SWR in shell and tube type SG

The most limited SWR accident in shell and tube SG is that multiple SG tubes are damaged by large amount of ejected steam jet. Once a SG tube is failed by crack or defect, steam is discharged from water side to sodium pool in steam generator. If crack size is very small, crack size becomes larger than before due to corrosive reaction products. It is self-wastage and described in Figure 2.

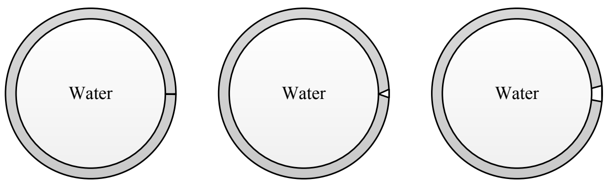

Figure 2. Simple sketch of self-wastage

Steam jet length becomes longer than before as the hole size becomes larger and larger. Finally, this steam jet can attack an opposite side tube. It is depicted Figure 3 and this phenomenon is called impingement wastage.

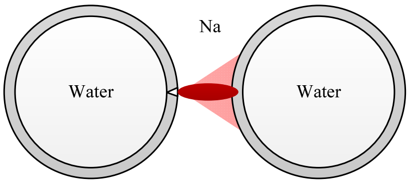

Figure 3. Simple sketch of impingement wastage phenomenon

In case large amount of steam are discharged into the sodium side due to large size failure, multiple tubes can be failure and sudden hydrogen pressurization can be occurred. Wide range of steam leak rate can be divided by four categories like as Table 1.

Table 1. Steam generator leak classification [12]

Steam leak	*Magnitude of leak*	*Main effect*
Micro	< 50 mg/s	Self wastage of the leaking tube
Small	50 mg/s ~ 10 g/s	Wastage of single adjacent tube
Intermediate	10 ~ 1000 g/s	Multiple tube damage, heating, slow hydrogen pressurization
Large	> 1000 g/s	Sudden hydrogen pressurization

Studies for wastage phenomenon have been performed in US, France, Japan, India, and Korea. General physics and model were established and numerical calculation can be possible [13].

One of the major research fields of SWR in shell and tube type SG is detection. Various methods such as chromatograph, cover gas thermal conductivity cell, cover gas pressure detector, rhometer, and hydrogen detector have been studied. In general, hydrogen detection method is being used to detect steam leak in shell and tube SG. In addition, acoustic detection is being considered promising method because of its very rapid detection speed. Acoustic detection methodologies are studied in US[1], Japan[8,14,15], Korea[10], and France[16].

3. Necessity of research of SWR in PCSG

Various type of SGs such as shell and tube SG, helical coil SG, and double tube bundle SG are studied for application to the PGSFR. PCSG is also being considered to apply to the PGSFR.

3.1 Advantages of the PCSG

Length of shell and tube SG should be very long because superheated steam has to be made and this SG has ineffective heat transfer ability. In addition, this type of SG has possibility of tube failure propagation because of the wastage. SWR risk is inevitable in shell and tube SG.

Double-walled SG tubes [17] are used to avoid SWR possibility in JSFR. However, heat transfer effectiveness is reduced in this type of SG tube because of presence of inert gas between tube walls.

Brayton cycle is also studied some research group [18~21] to totally exclude the SWR. But huge amount of design change must be followed if the Brayton cycle is applied to the PGSFR.

On the other hand, size of the PCSG is very small comparing with shell and tube SG due to its large heat transfer area. Manufacturing cost is also reduced because of its small size. And the PCSG has more resistance of SWR because it doesn't have sodium pool in SG. If SWR is occurred in the PCSG, steam is discharged into single small tube, and it is expected that there is no SWR in the tube. And also it is not necessary to modify the PGSFR design by application of not the Brayton cycle but sodium and water into the PCSG. In addition, malfunction and accidents of SG can be treated more effectively than shell and tube SG by modularization of the PCSG. For example if SWR is happened in the PCSG, steam leak will be detected rapidly by acoustic detection in header of the PCSG, and damaged and extra modular PCSG are isolated and connected, respectively. It's simple management of the SWR without reactor trip.

3.2 Safety issues for SWR in PCSG

Wastage and detection of SWR for shell and tube SG have being studied continuously. However, there is no research about these for the PCSG. Typically Brayton cycle is applied to the PCSG using CO_2 or N_2 gas and these had been studied in France, US, and Korea. Research for the Brayton cycle in France is performing using by N_2 gas. This PCSG system will be applied to ASTRID [18]. CO_2-water reaction is studied using SNAKE facility in ANL [19]. In Korea, CO_2-water reaction also had been studied. Wastage and self-plugging phenomena was tested in this research [20.21]. In addition, acoustic detection in the PCSG is studied in Sweden [22]. However, it is not for sodium-water system but for waterN2-water system.

Now, there are no any experimental results or data about SWR in the PCSG. There are no quantitative evidences about safety advantages of the sodium-water system PCSG even though the PCSG has more resistance to SWR. Therefore it is necessary to study SWR for the PCSG experimentally. Safety issues of SWR for the PCSG are as follow:

- What phenomenon is occurred in small tube when SWR is occurred?
- What condition results in maximum wastage damage?
- Acoustic detection is available in the PCSG?

First of all, we don't know what phenomena are happened in single small tube when water is injected into sodium tube. SWR is occurred inside of tube if very small amount of water is injected. If then, is the integrity of PCSG ensured? Wastage phenomenon can threaten the PCSG integrity? If wastage can break the PCSG, how this damage propagate? If large amount of water is injected, SWR will be occurred in the PCSG header. If then, can acoustic detection is applicable? How long time is available for taking mitigation action? We don't know answers about above questions. Therefore, SWR experiment for the PCSG is planned to solve above safety issues.

4. Preparation of SWR in single tube experiment

Strong point of the PCSG against to SWR accident comparing with shell and tube SG is as followed.

- Reduced impingement wastage due to very short target distance
- Exclusion of multiple tube damage by wastage
- Effective accident management by modularization of the PCSG
- Low background noise by laminarization of SG flow caused by small tubes

Above items are verified experimentally to apply the PCSG to the PGSFR. Therefore SWR experiment in single tube is planning now to show above strong point. Flow patterns are predicted like as Figure 4 when steam jet is injected into the small tube through crack. If steam injection rate is lower than certain value, bubbly or slug flow is developed within small tube. In this case, SWR is occurred inside the small tube and it is expected that tube wall is damaged by wastage. On the other hands, there is no SRW inside the small tube if steam injection rate is higher than certain value. This is because sodium within small tube is expelled both end side of the tube by high pressure injection. These flow patterns depend on crack size.

Water-air two phase flow experiment is planned before performing sodium-water reaction tests. Purposes of this fundamental test are visualization of two-phase flow pattern when one phase flows downward and other phase is injected side of tube. This test helpful in doing SWR experiment and obtaining insight with the SWR in small tube because SWR can't be visualized and sodium is opaque. Fundamental test apparatus is designed like as Figure 5. This test apparatus is making. Fundamental test results will be applied to determination of SWR test matrix and conditions.

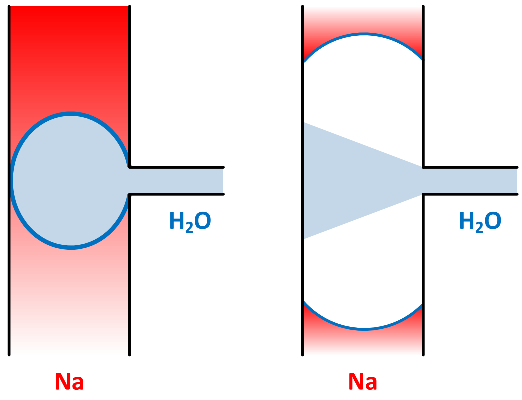

Figure 4. Anticipated flow pattern of SWR in small single tube

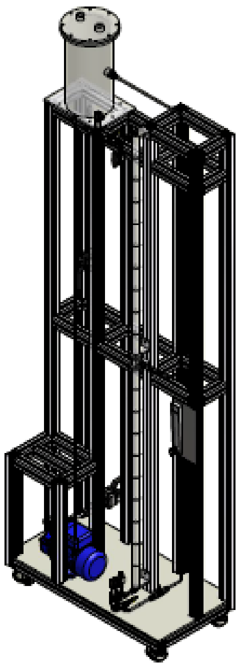

Figure 5. Fundamental test apparatus

5. Conclusion

SWR test for Shell and tube type steam generator had been performed with wide range of conditions in many countries. However, SWR test for the PCSG is not performed until now. SWR test for the PCSG must be carried out to solve following safety issues. It is necessary to apply the PCSG to the PGSFR.

- What phenomenon is occurred in small tube?
- What condition causes maximum wastage damage?
- Acoustic detection is available in the PCSG?

Fundamental test using water and air is designed before SWR experiment in single small tube. This test apparatus is constructing. Fundamental tests will be performed to visualize two-phase flow when water flows downward and air is injected side of the tube. And results of the tests will be applied to design SWR experiment apparatus and determine test matrix and conditions.

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