Preliminary Development of a Copper Bonded Steam Generator for minimizing a Sodium-Water Reaction

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has performed research and development on the Sodium-cooled Fast Reactor (SFR) as a next-generation reactor. The sodium has good thermal-hydraulic characteristics, but it has a strong tendency to react chemically with other materials. The Sodium-Water Reaction (SWR), which produces high heat and hydrogens, is one of the important phenomena. This SWR accident caused by a tube rupture in the steam generator has been a very important issue related to the safety and economic efficiency of the SFR.

In order to mitigate the consequence of the SWR accident, KAERI employed the Sodium-Water Reaction Pressure Relief System (SWRPRS) concept. On the other hand, KAERI has researched for a new type of a steam generator which minimizes the SWR accident.

In this paper, several candidates of steam generator concept which are developed to minimize the SWR accident are introduced. The Copper Bonded Steam Generator (CBSG) is selected as an optimal steam generator among the candidates. This paper contains a current status of development studies such as sizing calculation and preliminary design of the CBSG.

2. Candidate Steam Generator Concepts

2.1. Double Walled Tube Steam Generator (DWTSG)

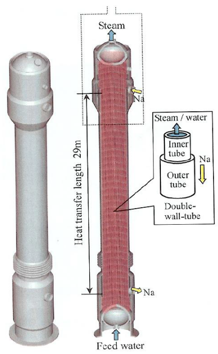

Fig. 1. JSFR DWTSG schematics

DWTSG has double walled tubes as a heat transfer tube to reduce the SWR occurrence frequency [1]. If the SWR accident occurs in DWTSG, it can be detected through the gap between the outer tube and the inner tube (Fig. 1). DWTSG was used in many fast reactors such as EBR-II and JSFR. However, several issues are still remaining such as heat transfer performance drop or prediction through the gap.

2.2. Double Tube Bundle Steam Generator (DTBSG)

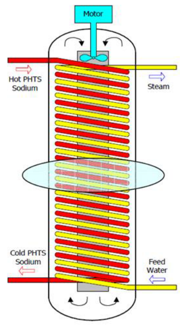

Fig. 2. DTBSG schematics

DTBSG has independent tube bundles for sodium-side and water-side [2]. The shell-side is filled with the inert heat transfer fluid such as lead-bismuth. The inert fluid has no chemical reactivity with other materials. Therefore, a chemical reaction will not occur while a heat transfer tube ruptures. The tube rupture can be detected by monitoring the shell-side pressure. Structure and design factors of the DTBSG are complex because three fluids flow through it.

2.3. Copper Bonded Steam Generator (CBSG)

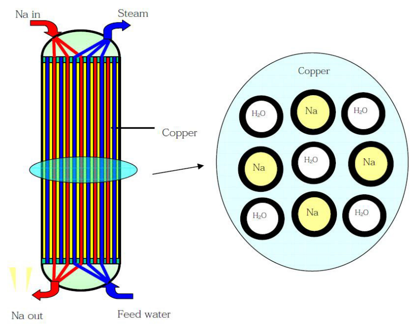

Fig. 3. CBSG schematics

CBSG consists of sodium tubes, water tubes, and copper matrices between sodium and water tubes [2]. The early design of CBSG in the 1950s has poor heat transfer performance. NNC and JAEA suggested the new design of diffusion-bonded CBSG by Hot Isostatic

Pressing (HIP) process [3]. CBSG has a triple barrier to prevent the SWR accident.

3. Heat Transfer Performance

Heat transfer performance of each candidate steam generator was quantitatively evaluated by comparing the heat transfer performance of Single Walled Tube Steam Generator (SWTSG). The thermal resistance of each steam generator was calculated with the 1-dimensional thermal resistance model as shown in Fig. 4 [4].

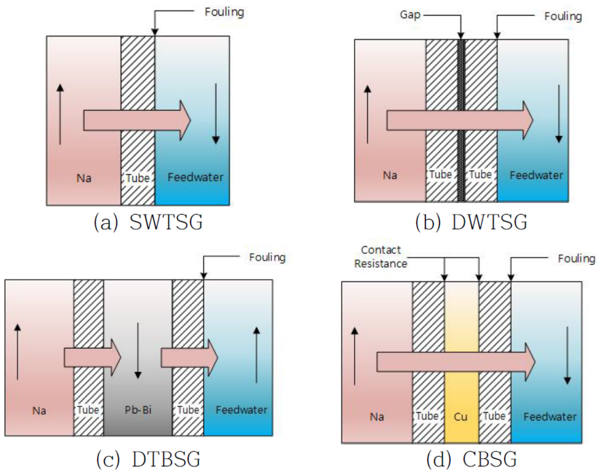

Fig. 4. One-dimensional model for heat transfer performance evaluation

For the total thermal resistance calculations, the convection resistance (R_{CV}), the conduction resistance (R_{CD}), the fouling resistance (R_{foul}) and/or the gap resistance (R_{gap}) are taken account. Dittus-Boelter correlation was used for calculating the convective heat transfer resistance. The fouling coefficient and gap coefficient are assumed to be 4.76x10^{-5} m^2·K/W and 1.0x10^{-4} m^2·K/W [1]. The thermal contact resistance coefficient of CBSG is assumed to be the same as the gap coefficient (1.0x10^{-4} m^2·K/W).

$$R_{CV} = \frac{1}{hA_{HT}} \sim \frac{D_h^{0.2} A_c^{0.8} \mu^{0.4}}{k^{0.6} \dot{m}^{0.8} C_p^{0.4} A_{HT}} \quad (1)$$

$$R_{CD} = \frac{t}{kA_{HT}} \quad (2)$$

$$R_{foul} = \frac{R^{"}}{A_{HT}} \quad (3)$$

$$R_{gap} = \frac{R^{"}_{gap}}{A_{HT}} \quad (4)$$

Required total heat transfer area for the same thermal power are shown in Table 1. The required heat transfer area is normalized by the heat transfer area of SWTSG.

Table 1. Required heat transfer area of candidate SGs

SG type	SWTSG	DTBSG	DWTSG	CBSG
required heat transfer area	1	1.73	1.74	2.17

4. Sodium-Water Reaction Occurrence Frequency

Two scenarios of SWR accident should be considered to evaluate the SWR occurrence frequency. One is the failure of the heat transfer tube surface, and the other is the failure of the welding part of the heat transfer tube to the tube sheet. The SWR occurrence frequency of each candidate SG was calculated based on the failure frequency and the total number of the heat transfer tube surface and welding part (Fig. 5) [4]. The SWR occurrence of CBSG is significantly low compared to other types of SG because it has no welding part of the heat transfer tube to the tube sheet which contributes a large portion of the SWR occurrence.

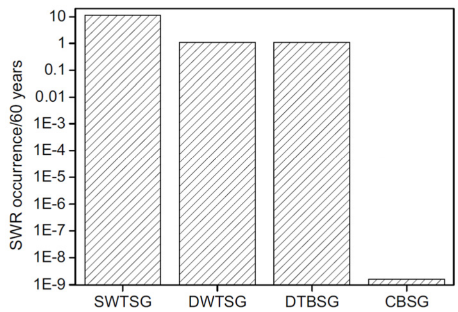

Fig. 5. SWR occurrence frequency comparison

5. Preliminary sizing calculation

CBSG is selected as an optimal steam generator because it has the lowest SWR occurrence frequency among the candidates. Detailed design factors were considered such as counter-flow heat exchanger versus cross-flow heat exchanger, rectangular tube versus circular tube, etc. A cross-flow heat exchanger is selected because it is easy to separate the sodium and water header location. The header separation is good for preventing the SWR accident caused by the header failure. The rectangular heat transfer tube is selected for the sodium-side tube, and the circular heat transfer tube is selected for the water-side tube. Table 2 and Fig. 6 shows the preliminary sizing results and 3D modeling of CBSG.

Table 2. Preliminary CBSG sizing results

SG type	Unit	SWTSG (PGSFR)	CBSG
tube length	[m]	25.1	26.2
SG diameter	[m]	1.15	1.6 x 1.6
tube OD/ID	[mm]	17.3/12.7	17.3/12.7
number of tubes	[-]	769	4356
pitch to diameter ratio	[-]	1.867	1.35

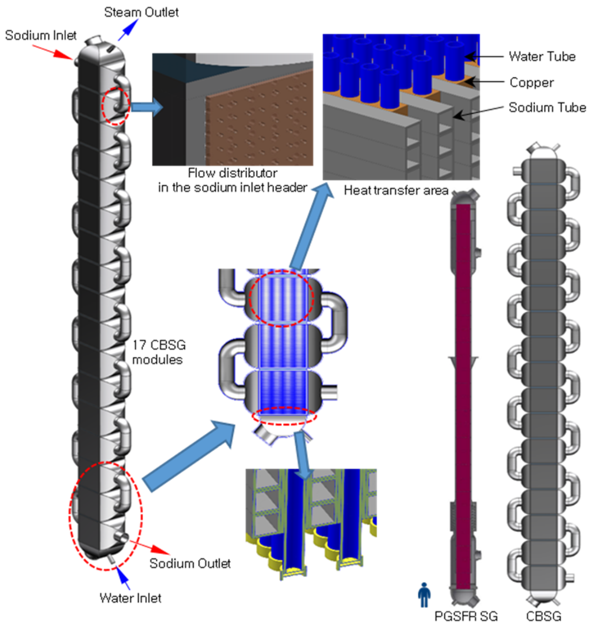

Fig. 6. Preliminarily 3D modeling of CBSG

6. Conclusions

Several candidates of steam generator type were reviewed for minimizing SWR. Heat transfer performance and the SWR occurrence frequency of the candidates were analyzed. CBSG was selected for its low frequency of SWR occurrence. The preliminary sizing and 3D modeling were performed for 196 MW CBSG.

ACKNOWLEDGMENTS

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