Thermal-Hydraulic Performance Analysis of an IHX-Combined Steam Generator with Serpentine Tube Bundles

Hyungmo Kim[a*], Namhyeong Kim[b], Jung Yoon[a], Dong Eok Kim[c], Jaehyuk Eoh[a], and Moo-Hwan Kim[b]
[a]*Korea Atomic Energy Research Institute, Daejeon, South Korea*
[b]*Division of Advanced Nuclear Engineering, POSTECH, Pohang, South Korea*
[c]*School of Energy Systems Engineering, Chungang University, Seoul , South Korea*
**Corresponding author: hyungmo@kaeri.re.kr*

1. Introduction

Sodium-cooled fast reactors (SFRs) have been developed as one of the promising type of NPPs among the fourth-generation (Gen-IV) nuclear systems. Although SFR systems could dramatically improve the inherent safety of the primary circuit by using liquid sodium as a coolant, the public is still afraid of the sodium-water reaction (SWR) due to the high chemical reactivity of sodium. Therefore, in order to meet the public acceptance criteria, it is necessary to adapt the concept to prevent SWR on a steam generator in a Rankine cycle.

An IHX-combined steam generators were firstly proposed as an alternative of intermediate heat transfer system in a loop type reactor [1]. This integrated steam generator has an intermediate fluid in a shell, which is unreactive with both water and sodium. This integrated steam generators can be an effective option for prevention of SWRs, and they studied so far are helical tube types [2,3].

In this study, we report thermal-hydraulic performance analysis results of an IHX-combined steam generator with a serpentine tube configuration (serpentine tube type IHX-combined steam generator, S-ICSG) using a dedicatedly developed one-dimensional computer code for a specific design evaluation of the S-ICSGs (SPINS-S, sizing and performance analyzer for an integrated steam generator – serpentine tube arrangement) [4].

2. Methods and Results

2.1 Design Features of S-ICSG

Fig. 1 represents a scaled configuration of S-ICSG designed using SPINS-S. Serpentine tubes have lower volume efficiency than helical configuration. However, the circulation of the intermediate fluid is very simple and effective, and the unfavorable volume efficiency can be overcome by advantage of modularization. Table I represents the detailed design specifications for the S-ICSG. Its thermal capacity is about 96.66 MWt (i.e., a 1/16 modularized SG unit of 600 MWe NPP). To realize this S-ICSG, two S-ICSG units are needed. One is the upward-region unit and the other is the downward-region unit.

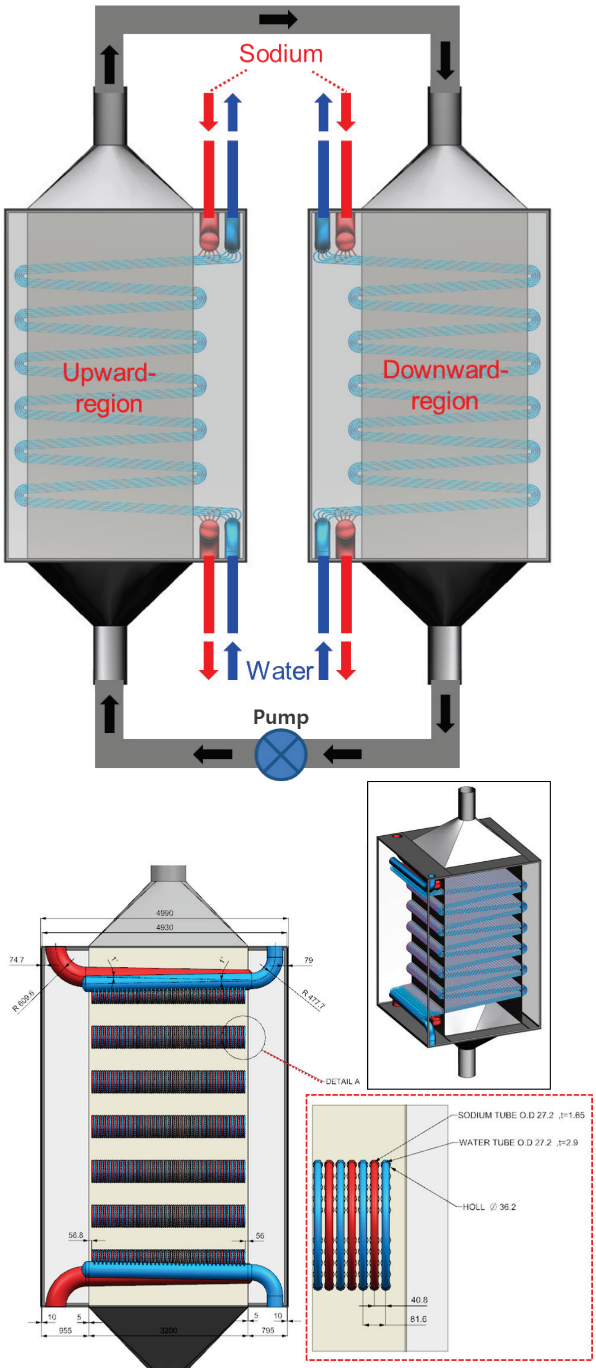

Fig. 1. Configuration of S-ICSG (designed by SPINS-S).

Table I: Design Specification of the S-ICSG unit

Design Parameter	Value
Length of tubes [m]	40.0
Number of hot tubes [ea]	190
Number of cold tubes [ea]	190
Number of tubes in a bank [ea]	5
Number of tube layers [ea]	38
Number of tube bends [ea]	11
Outer diameter of tube [mm]	27.2
Thickness of hot tube [mm]	1.65
Thickness of cold tube [mm]	2.9
Tube inclination angle [°]	3.0
Pitch-to-diameter [-]	1.5

The steam generator shell is filled with an intermediate fluid, which is unreactive with water and sodium, such as a lead-bismuth alloy. We choose sodium and water as the working fluids on the tube-side, and Lead-Bismuth Eutectic alloy (LBE) as the working fluid on the shell-side. Table II is the thermal-hydraulic boundary conditions for evaluations

Table II: Analysis conditions

Parameter	Value
Sodium mass flow rate [kg/s]	522.88125
Sodium inlet temperature [°C]	510.0
Steam/water mass flow rate [kg/s]	43.08125
Steam outlet temperature [°C]	471.2
LBE mass flow rate [kg/s]	200.000

2.2 Introduction to the computer code (SPINS-S)

The SPINS-S code is based on conventional techniques of a thermal sizing and performance analysis for a shell-and-tube type cross-flow heat exchanger among different fluids. We choose Lead-Bismuth Eutectic alloy (LBE) as the working fluid on the shell-side. Detailed information including physical models, correlations, and calculation process flow were described in our previous paper [4].

2.3 Sensitivity test of the number of nodes

Fig. 2 shows the sensitivity test result of the number of nodes. The x-axis means the number of nodes per every single straight tube section. As a result, the number of nodes was negligible to make some difference in the calculated results. However, in the case of water/steam tubes, relatively large control volume made worse performance during convergence process. We recommend over 40 control volumes per a single straight tube.

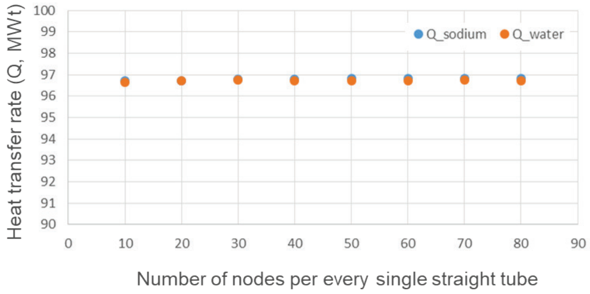

Fig. 2. Sensitivity test result of the number of nodes.

2.4 Flow rate effect of an intermediate fluid

S-ICSG is very easy to make a promising flow rate of the intermediate fluid because of separation of two regions. Fig. 3 represents LBE flow rate effect. Larger flow rate can make higher heat transfer performance until the flow rate of 160 kg/s. However, in the case of over 160 kg/s, improvement of heat transfer performance is not big deal as increase of LBE flow rates. It can be caused the limit of temperature at the outlet sections.

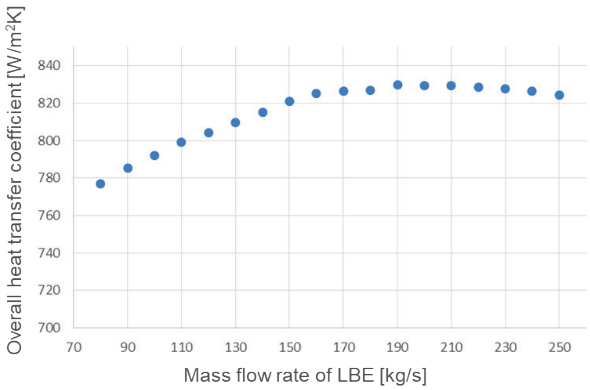

Fig. 3. LBE flow rate effect to overall heat transfer coefficient.

2.5 Temperature distributions

Fig. 4 and Fig. 5 show temperature distribution of the S-ICSG unit in the upward-region and the downward-region, respectively. In Fig. 3 and Fig. 4, x-axis means longitudinal location based on tube-side flows. LBE temperatures are locally stepwise profiles, and it is caused by the bending effects from serpentine tube configuration.

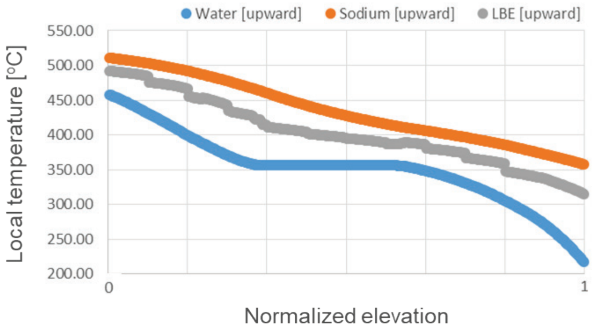

Fig. 4. Temperature distribution of the S-ICSG in the 'upward' unit (at LBE flow rate = 200 kg/s).

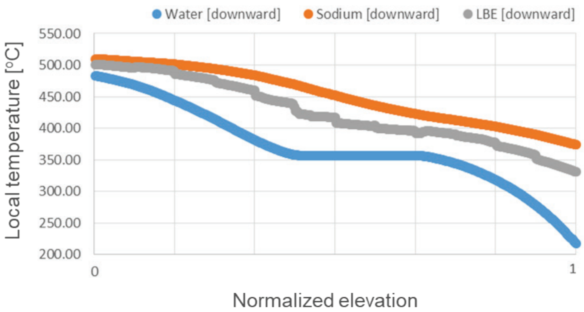

Fig. 5. Temperature distribution of the S-ICSG in the 'downward' unit (at LBE flow rate = 200 kg/s).

3. Conclusions

We designed and evaluated an integrated type steam generator called as S-ICSG having three heat transfer fluids. It has the advantage of using the proven power conversion system of the existing Rankine cycle, and it can prevent the SWR by adopting the inactive intermediate fluid with both sodium and water. In addition, it is advantageous in modularity, instead of the low volume efficiency compared with the conventional steam generator. In our present analyses using our one-dimensional computer code (called as SPINS-S), optimal LBE flow rate was about 200 kg/s in the view of heat transfer performance. Through the temperature distribution analyses, we observed locally stepwise temperature profiles of LBE. We will carry out further analyses and design optimization in the near future.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Energy Research Infrastructure Program through the National Research Foundation of Korea (NRF) by the Ministry of Science, ICT and Future Planning (2016M2B2B1944980).

REFERENCES

[1] K. Miyazaki and H. Horiike, Advanced IHX-SG Combined FBR System Designs and Basic Experiments, 10th Pacific Basin Nuclear Conference, Kobe, Japan, October 20-25, 1996.
[2] Y.S. Sim et al., A New LMR SG with a Double Tube Bundle Free from SWR, Journal of the Korean Nuclear Society, Vol. 35(6), pp. 566-580, 2003.
[3] Y.S. Sim and S.-O. Kim, Development of an Advanced LMR Steam Generator Free from SWR with a Double Tube Bundle Configuration, 13th International Conference on Nuclear Engineering, Beijing, China, May 16-20, 2005.
[4] H. Kim et al., Development of a Thermal-Hydraulic Analysis Code for an IHX-Combined Steam Generator with Serpentine Tube Bundles, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 17-18, 2018.