Preliminary Design Evaluation of IHTS-Combined Steam Generator Concepts for a Sodium-cooled Fast Reactor

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1. Introduction

Development of fourth-generation (Gen-IV) nuclear systems has been underway for the purpose of an efficient use of uranium resources and a substantial transuranics (TRU) reduction [1]. Among those kinds of innovative reactor systems, a sodium-cooled fast reactor (SFR) has been taken into account as one of the most promising types of fast reactors to meet the essential goals of Gen-IV system. An SFR can have enhanced safety features rather than a pressurized water reactor (PWR), but it would have worse cost-effectiveness coming from a potential sodium water reaction (SWR) in a steam generator (SG). To overcome the weak points, several researchers have suggested innovative concepts of IHTS-Combined Steam Generators (ICSGs) for the purpose of potential elimination of intermediate heat transfer system (IHTS) by incorporating medium heat transfer fluid between primary sodium system and steam/water system [2-5].

The intermediate heat transfer medium employed in ICSG concepts should be inactive with sodium as well as water/steam to avoid an SWR, which is one of the promising features free from essential risk of SWR. However, thermal-hydraulic behaviors in ICSGs are much more complicated than those of conventional SGs. Therefore, there are still lots of practical issues and obstacles for its commercial use. In this study, we evaluated the proposed ICSG types with the conceptual configuration and natural-born features. Based on the results of this work, an improvement of the ICSG design concepts will be carried out as a future work.

2. Conceptual Design Evaluation

2.1 Type of ICSG

We choose 5 representative configurations of ICSGs suggested until now as shown in Fig. 1. Advanced intermediate heat exchanger (AIHX) was proposed by Miyazaki [2]. Sodium was used as the intermediate medium, but it can be replaced by other materials that do not react with sodium and water. Primary sodium flows downward, and water/steam flows through helically coiled tubes as shown in Fig. 1(a). Fig. 1(b)-1(e) represent 4 different kind of double tube bundle steam generators (DTBSGs) developed in Korea Atomic Energy Research Institute (KAERI) [3-5]. It practically removes the SWR possibility by a double installation of the heat transfer tube bundles in an SG shell. The SG shell is filled with a medium fluid which is chemically stable with water and sodium, such as a lead-bismuth alloy. DTBSGs have a pump to circulate the medium fluid inside the steam generator shell.

The heat transfer characteristics of each type are very different depending on the arrangement and configuration of the heat transfer tubes. We performed a conceptual design evaluation of heat transfer characteristics using the simple one-dimensional approach with notations and assumptions as follows.

- $T_{s,h}$: Inlet sodium temperature
- $T_{s,c}$: Outlet sodium temperature
- $T_{w,c}$: Inlet water temperature
- $T_{w,h}$: Outlet water temperature
- Assume $T_{s,h} > T_{w,h} > T_{s,c} > T_{w,c}$.
- Consider as steady-state conditions.
- Temperatures of sodium and water are linearly changed.
- The conductivity of a medium fluid is good enough.

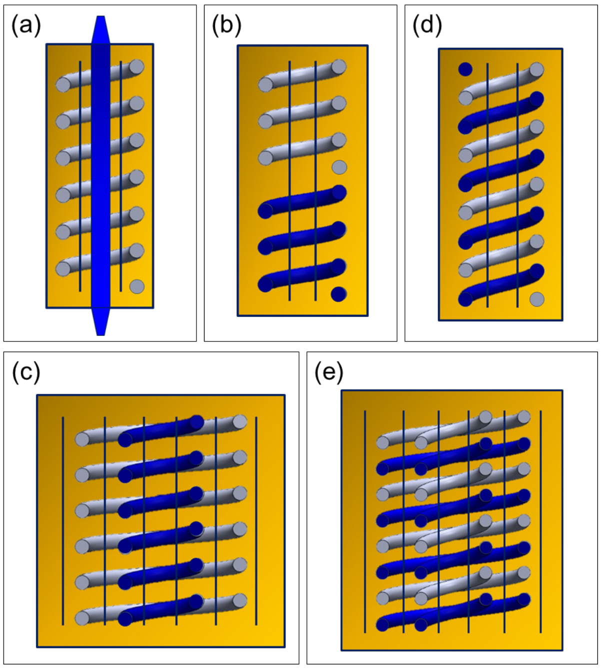

Fig. 1. The configurations of the proposed ICSG Types:
(a) AIHX,
(b) vertically separated DTBSG,
(c) radially separated DTBSG,
(d) integrated single-region DTBSG, and
(e) integrated double-region DTBSG.

2.2 Evaluation results

Total 6 possible cases of the conceptual design of ICSGs are evaluated as shown in Fig.2 - Fig. 7. AIHX (Fig. 2), the radially separated DTBST (Fig. 5) and the integrated double-region DTBST (Fig. 7) show typical temperature distributions behaviors, although they should have different efficiency and flow path of medium fluid. The vertically separated DTBSG (Case I and II) and the integrated single-region DTBST have the path of medium fluids without heat transfer (dash line). Among them, the vertically separated DTBSG (Case II) shows downward flow direction of water, and this is not efficient considering the density difference between steam and water, so Case I is more practical than Case II (Fig. 3 and Fig. 4).

The integrated DTBSGs have a low sensitivity to medium fluid flow rate and have an advantage of ensuring efficient heat transfer even at low flow rates with small pumping power. However, in the case of integrated single-region DTBSG, the reverse phenomenon of temperatures occurs at low elevation and it makes the efficiency decrease (Fig. 6). On the other hand, although the integrated double-region DTBSG has a complicated configuration, this temperature reversal phenomenon can be eliminated and efficiency should be increased rather than the integrated single-region DTBSG as shown in Fig. 6 and Fig. 7.

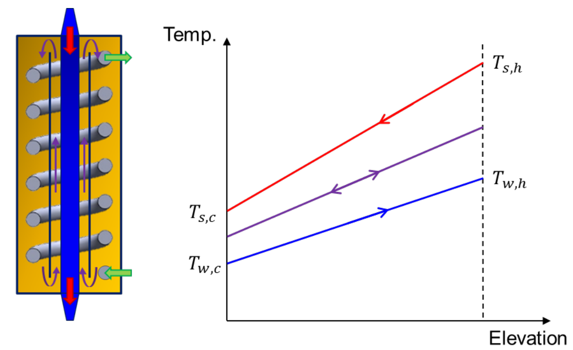

Fig. 2. Conceptual design evaluation of AIHX.

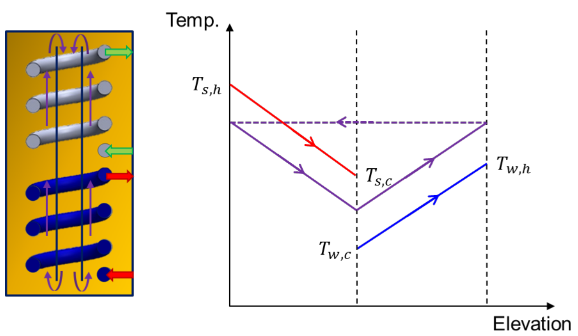

Fig. 3. Conceptual design evaluation of vertically separated DTBSG (Case I).

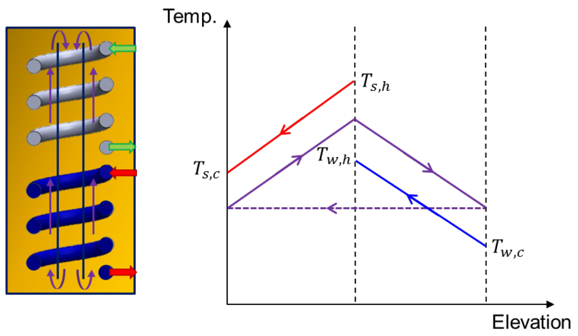

Fig. 4. Conceptual design evaluation of vertically separated DTBSG (Case II).

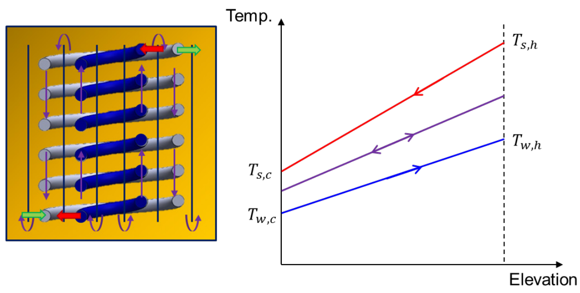

Fig. 5. Conceptual design evaluation of radially separated DTBSG.

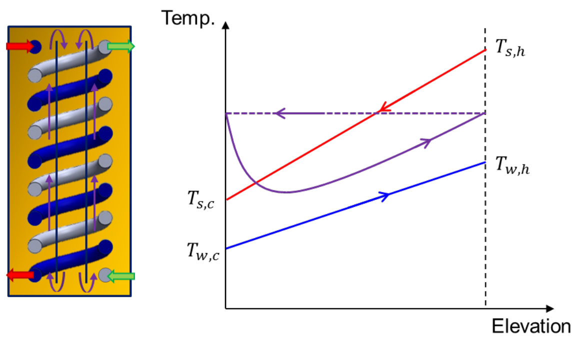

Fig. 6. Conceptual design evaluation of integrated single-region DTBSG.

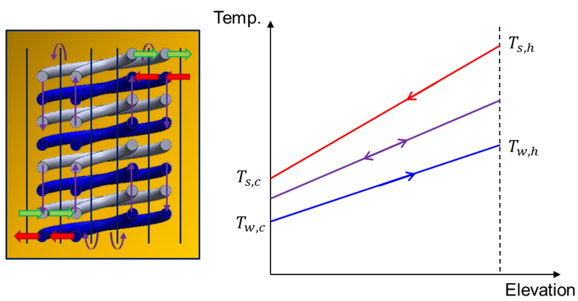

Fig. 7. Conceptual design evaluation of integrated double-region DTBSG.

2.3 Advantages and disadvantages by ICSG types

The each ICSG type has unique features, so it is necessary to select the optimal configuration and flow directions to the situation. Table I represents the advantages and disadvantages of each type of ICSG proposed until now.

Table I. Advantages and disadvantages by ICSG type.

	Pros.	Cons.
AIHX	Natural convection, Simple configuration, Easy to design	Low space efficiency
Vertically separated DTBSG	High space efficiency, Also applicable to pool type reactor	Need to high flow rate, Stratification without pumping power
Radially separated DTBSG	High space efficiency, Easy to design	Need to high flow rate
Integrated single-region DTBSG	High efficiency at low flow rate, Simple configuration	Partially temperature reversal
Integrated double-region DTBSG	High efficiency at low flow rate	Complicated configuration

3. Conclusions

The IHTS-Combined Steam Generator has the advantage of using the proven power conversion system of the existing Rankine cycle as it is compared to the adaptation of new gas Brayton cycle while it can prevent the SWR by adopting the inactive intermediate medium in both sodium and water. In this study, the temperature distributions of sodium, water, and medium fluids were evaluated by a simple one-dimensional approach to each ICSG concept of various configurations proposed so far, and the advantages and disadvantages of each type were analyzed. Based on this work, the more detailed ICSG design and evaluation will be carried out in the further study to improve the safety of SFRs.

ACKNOWLEDGMENTS

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