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# Development of a Thermal-Hydraulic Analysis Code for an IHX-Combined Steam Generator with Serpentine Tube Bundles

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## 1. Introduction

Development of fourth-generation (Gen-IV) nuclear systems has been underway for the purpose of an effective utilization of uranium resources and a minimal spent fuel waste [1]. A sodium-cooled fast reactor (SFR) has been considered as one of the most promising options to pursue these purposes of Gen-IV system. An SFR can have enhanced safety features by using liquid sodium as a coolant, but there is concern about unexpected events coming from a sodium water reaction (SWR) in a Rankine cycle steam generator.

Several prior researchers have suggested innovative concepts of the integrated type steam generators including an intermediate heat exchanger (IHX) for the purpose of inherently elimination of SWR by employing intermediate fluid between liquid sodium and steam/water system [2-4]. Especially, Sim *et al.* and Kim *et al.* proposed 4 types of steam generator with a double tube bundle configuration, and it practically removes the SWR possibility by a double installation of the helically coiled heat transfer tube bundles in a steam generator shell [2-4]. The steam generator shell is filled with an intermediate fluid which is unreactive with water and sodium, such as a lead-bismuth alloy. They had performed basic theoretical and experimental studies, but there is a lack of detailed research such as those on the arrangement of heat transfer tubes and chamber geometries and consideration of other shapes.

In this study, we propose a new IHX-combined steam generator with a serpentine tube configuration (Serpentine tube type IHX-Combined Steam Generator, S-ICSG), and reports the developed thermal-hydraulic analysis code for specific design evaluation of the S-ICSGs (SPINS-S, Sizing and Performance Analyzer for an Integrated Steam Generator – Serpentine tube arrangement).

## 2. Method

### *2.1 Configuration of S-ICSG*

S-ICSG has many serpentine tubes inside outer shell containing an intermediate fluid such as a lead-bismuth alloy. The tubes are divided into sodium tube and water tubes, and the outer diameter and number of the each tubes are the same for each fluid. The tube columns for each fluids are alternately arranged one by one to use the most of local heat transfer phenomenon. It always consists of pair units; one is for upward shell-side flow and the other is for downward shell-side flow. These two units are connected by ordinary piping, which means that the pumping method of the intermediated fluid is very conventional. Fig. 1 represents the schematic drawing of S-ICSG.

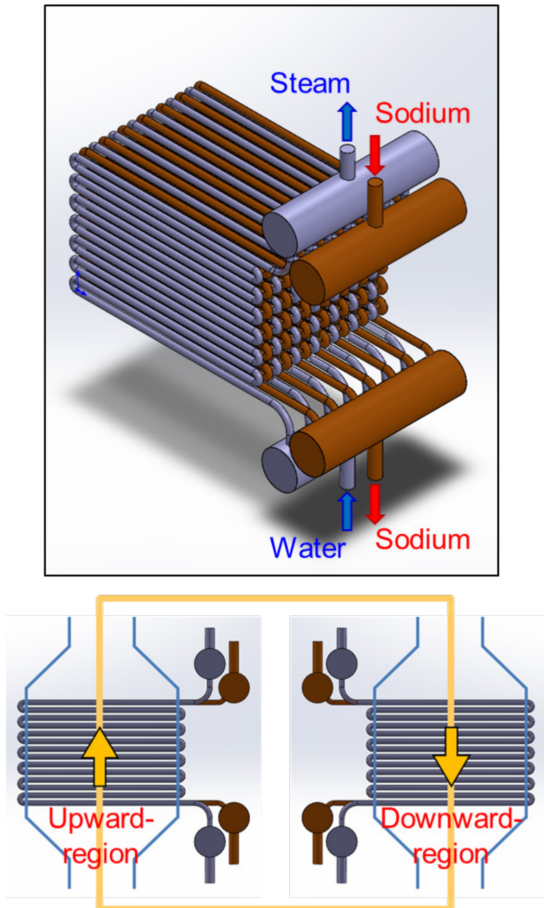


Fig. 1. Configuration of S-ICSG.

### *2.2 Physical Model for Numerical Calculation*

SPINS-S code can carry out thermal sizing and performance analysis for the shell-and-tube type cross-flow heat exchanger among three different fluids. We choose sodium and water as working fluids in the tube-side, and LBE as a working fluid in the shell-side. A simplified one-dimensional model is chosen to describe the steady state flow of the shell- and tube-sides. The physical model satisfies fundamental continuity equations of mass, momentum, and energy conservations described as Eqs. (1) ~ (3), where $\omega_s$, $\omega_{t1}$, $\omega_{t2}$ are the LBE mass flow rate, the sodium mass flow rate, and the water mass flow rate, respectively. The total pressure loss for each control volume is the summation of the frictional term ($\Delta P_{fric}$), accelerational term ($\Delta P_{acc}$), and gravitational term ($\Delta P_{grav}$). The terms $U$, $A$, $\Delta T_{LMTD}$ are overall heat transfer coefficient, heat transfer area, and the log-mean temperature difference (LMTD), respectively.

$$\omega_s = const, \omega_{t1} = const, \omega_{t2} = const \quad (1)$$

$$\Delta P_{tot} = \Delta P_{fric} + \Delta P_{acc} + \Delta P_{grav} \quad (2)$$

$$\Delta Q = U \cdot A \cdot \Delta T_{LMTD} \quad (3)$$

### *2.3 Correlations and Calculation Process*

For the thermal sizing, Lyon-Martinelli correlation (sodium), Dittus-Boelter correlation (water, single-phase), Chen correlation (water, two-phase), and Kalish-Dwyer correlation (LBE) are adopted. Table I and Table II summarize the heat transfer correlations and pressure drop correlation implemented in the code.

Table I. The heat transfer correlations adopted in SPINS-S.

| **Fluid** | **Correlation** |
|---|---|
| Sodium | Lyon-Martinelli |
| Water, single-phase | Dittus-Boelter |
| Water, two-phase | Chen |
| Lead-Bismuth | Kalish-Dwyer |

Table II. The pressure drop correlations adopted in SPINS-S.

| **Fluid** | **Correlation** |
|---|---|
| Sodium & Water, single-phase | Darcy friction factor formula |
| Water, two-phase | Homogeneous Equilibrium Model |
| Lead-Bismuth | Gunter-Shaw |

The flow chart of SPINS-S for thermal-sizing is represented in Fig. 2. After reading input values, heat transfer rate, enthalpy difference, pressure and temperature distributions are sequentially calculated in the upward-region. At this time, the inlet temperature of sodium is a convergence criteria, and the inlet temperature of LBE is assumed with an initial value between the outlet steam temperature and the inlet sodium temperature. And then, the calculation in the downward-region is performed in the same manner, and the water inlet temperature is a convergence criteria. The obtained outlet LBE temperature in the upward-region is used as the inlet LBE temperature in the downward-region. This calculation is repeated until there is only little difference between the outlet LBE temperature of the downward-region and the inlet temperature of the upward-region, we assumed as the initial value. If all convergence criteria through calculations, the total heat transfer rate is compared with the target heat transfer rate. Also, by taking the proper value of heat transfer tube length, we can figure out the calculated geometrical factors including total heat transfer tube length for the desired heat transfer rate.

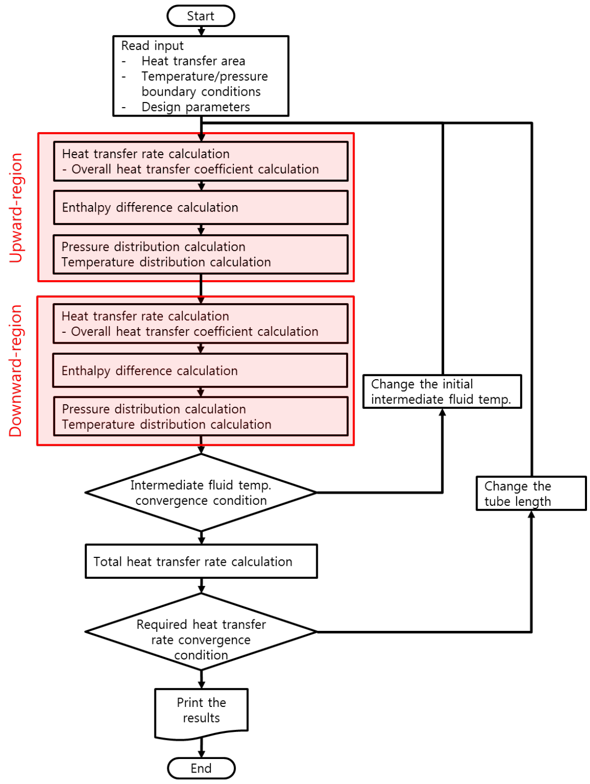


Fig. 2. The flow chart of SPINS-S.

## 3. Result and Discussion

### *3.1 Geometrical results*

It is very hard to perform benchmark calculations because the S-ICSG concept has the different configuration from the previously proposed ICSG concepts. So, we conducted a test thermal-sizing process on a 150 MWe heat capacity for improving our SPINS-S code. Table III shows the geometrical design results obtained from SPINS-S.

Table III. The geometry parameters using SPINS-S.

| **Parameter** | **Value** |
|---|---|
| Total tube length [m/ea] | 42.000 |
| Number of sodium tube in a region [ea] | 380 |
| Number of water tube in a region [ea] | 380 |
| Number of tube banks [ea] | 8 |
| Number of tube column [ea] | 76 |
| Number of tube rows [ea] | 5 |
| Outer diameter of sodium tube [m] | 0.0272 |
| Inner diameter of sodium tube [m] | 0.0239 |
| Outer diameter of water tube [m] | 0.0272 |
| Inner diameter of water tube [m] | 0.02214 |
| Tube inclined angle [°] | 3.0 |
| Longitudinal pitch to diameter ratio [-] | 1.5 |
| Transverse pitch to diameter ratio [-] | 1.5 |
| Height of shell [m] | 5.980 |
| Width of shell [m] | 5.243 |
| Depth of shell [m] | 6.342 |

### *3.2 Heat transfer Result*

Table IV represents the heat transfer results using SPINS-S. There is allowable difference between the target heat transfer rate and the calculated heat transfer rate.

Table IV. The heat transfer results using SPINS-S.

| **Parameter** | **Value** |
|---|---|
| Target heat transfer rate [MWth] | 193.53 |
| Heat transfer rate of sodium [MWth] | 193.276 |
| Heat transfer rate of water [MWth] | 193.419 |
| Sodium heat transfer rate in upward-region [MWth] | 103.246 |
| LBE heat transfer rate in upward-region [MWth] | 10.378 |
| Water heat transfer rate in upward-region [MWth] | 94.568 |
| Sodium heat transfer rate in downward-region [MWth] | 90.031 |
| LBE heat transfer rate in downward-region [MWth] | 10.501 |
| Water heat transfer rate in downward-region [MWth] | 98.851 |
| Heat transfer area of IHX [$m^2$] | 2727.61 |
| Heat transfer area of SG [$m^2$] | 2727.61 |
| Heat flux on IHX [$kW/m^2$] | 70.859 |
| Heat flux on SG [$kW/m^2$] | 70.912 |
| Overall heat transfer coefficient [$kW/m^2$-K] | 0.869702 |
| Temperature difference (LMTD) [°C] | 81.580 |
| Total thermal resistance [K/MW] | 0.071481 |

### *3.3 Fluid information*

Table V shows the fluid boundary conditions and the related results using SPINS-S.

Table V. Fluid boundary conditions and calculation results using SPINS-S.

| **Parameter** | **Value (upward)** | **Value (down ward)** |
|---|---|---|
| Sodium mass flow rate [kg/s] | 1045.763 | |
| Sodium inlet temperature [°C] | 510.3 | 510.0 |
| Sodium outlet temperature [°C] | 355.8 | 374.9 |
| Water mass flow rate [kg/s] | 86.162 | |
| Water inlet temperature [°C] | 217.0 | 217.0 |
| Water outlet temperature [°C] | 456.5 | 486.3 |
| LBE mass flow rate [kg/s] | 500.0 | |
| LBE temperature at top [°C] | 488.8 | 488.8 |
| LBE temperature at bottom [°C] | 342.2 | 342.2 |

## 4. Conclusions

The new IHX-Combined Steam Generator concept having serpentine tube configuration (S-ICSG) was proposed in this work. It has the advantage of using the proven power conversion system of the existing Rankine cycle while it can prevent the SWR by adopting the inactive intermediate fluid with both sodium and water. We developed the thermal-hydraulic performance analysis code, and the test results were described. Based on this work, improvement of iterating time and robustness of the code will be conducted in the near future, and the more detailed S-ICSG design and evaluation will be carried out using the SPINS-S code.

## ACKNOWLEDGMENTS

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