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Development of a One-Dimensional Analysis Code for Integrated Steam Generator with Helical Tubes Using a Three-Fluid Heat Transfer System

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1. Introduction

Because a sodium-cooled fast reactor (SFR) uses sodium as the primary coolant, a sodium-water reaction (SWR), which is a threat to reactor safety, can occur. Therefore, an intermediate heat transfer system (IHTS) is used to prevent the release of radioactive sodium due to the SWR. However, the SWR potential between the secondary sodium and water in the steam generator still exists.

To overcome this problem, an integrated steam generator concept, an IHX-combined steam generator (ICSG), has been developed [1]. The ICSG consists of a shell filled with an intermediated fluid, primary sodium tubes, and tertiary water/steam tubes. Therefore, the heat transfer path is not sodium-water, but sodium-intermediate fluid-water. As an intermediate fluid, lead-bismuth, which does not react with either sodium or water, is used, and thus the presence of intermediate fluid prevents direct contact between sodium and water. It can significantly reduce the probability of an SWR.

Miyazaki and Horiike developed the concept of an advanced intermediate heat exchanger (AIHX) [2]. As AIHX is intended to simplify the IHTS, sodium is used as the intermediate fluid in the AIHX; however, other materials that do not react with sodium and water can be substituted. Sim *et al.* developed a double tube bundle steam generator (DTBSG) concept to prevent an SWR and proposed four different types of tube configuration [3]. Kim and Baek performed one-dimensional performance analyses of DTBSG [4].

In this paper, a detailed design of a helical tube type ICSG (H-ICSG) including tube and chamber arrangement is developed. And, a one-dimensional performance analysis code for the H-ICSG, called a 'Sizing and Performance Analyzer for an Integrated Steam Generator – helical tube (SPINS-H)', is explained.

2. Helical Tube Type ICSG

H-ICSG has the structure shown in Fig. 1. Each helical tube is concentric with a bobbin cylinder and rolled up with the almost same inclined angle. Sodium tube rows alternate with water tube rows, and all tube rows are divided into two heat transfer zones. Chambers are located above and below the heat transfer zones, and three chambers for each fluid are placed at equal intervals to reduce the temperature fluctuation. This arrangement

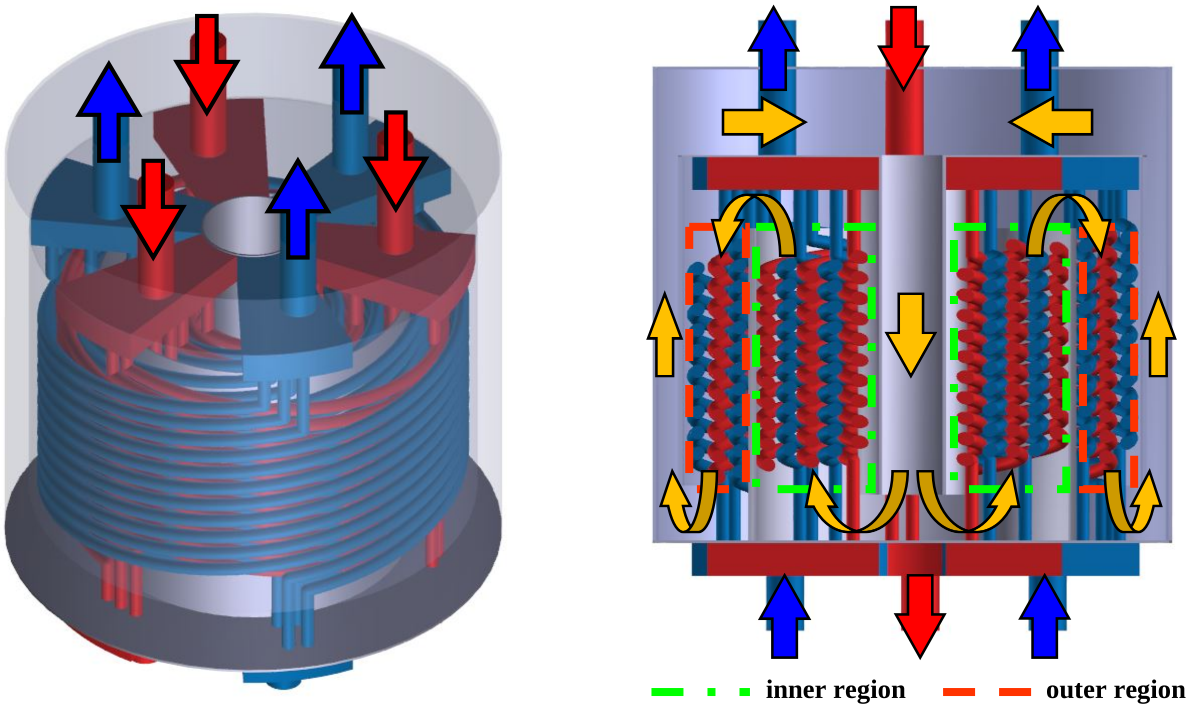

Fig. 1. Schematic (left) and cross-sectional view (right) of H-ICSG

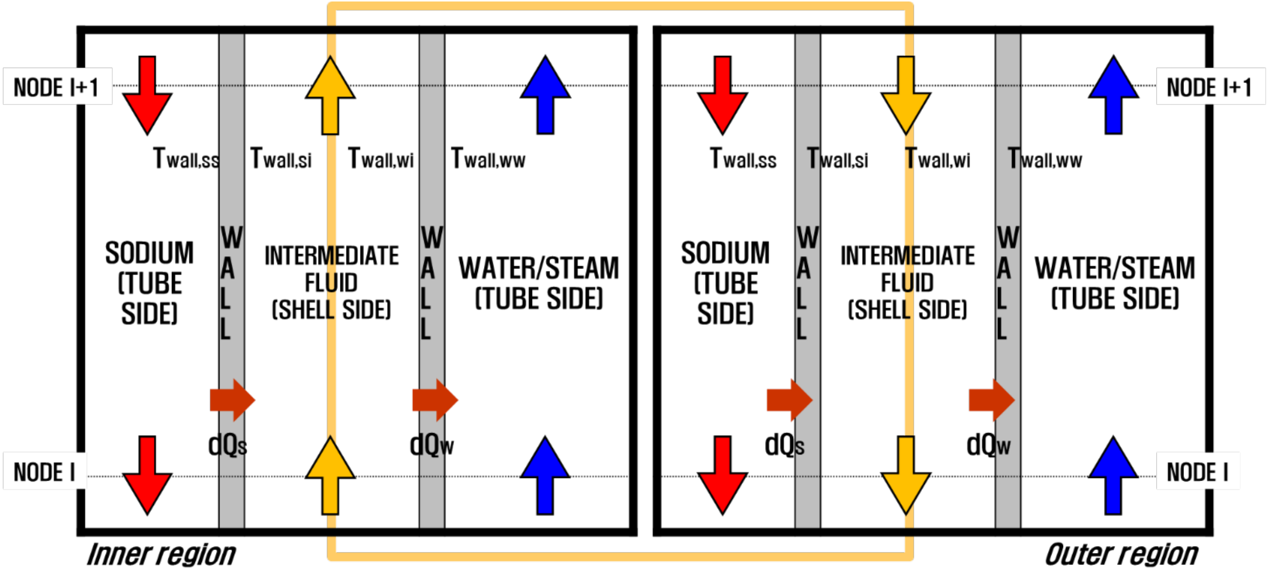

Fig. 2. One-dimensional heat transfer model of H-ICSG

also reduces the additional tube length for connection to the chambers. The intermediate fluid is pumped from inside of the bobbin cylinder and rises along the inner heat transfer region and descends along the outer heat transfer region. The fluid, which is passed through the outer region, rises along the outermost flow path and circulates back to the bobbin cylinder.

3. Numerical Analysis Method

The one-dimensional calculation is performed along the vertical direction of the steam generator with respect to three fluids because the diameter of tube is very small compared to the length. The heat transfer model in the control volume used in H-ICSG is described in Fig. 2. The tube-side sodium and water flow in the downward and upward directions, respectively, and the shell-side intermediate fluid flows upwards in the inner region and downwards in the outer region.

The equations used in the heat transfer rate calculation are as follows. The equations are identical with the heat transfer between two fluids in a shell-and-tube heat exchanger. Heat transfer among the three fluids occurs simultaneously with the heat transfer between the sodium-intermediate fluid and intermediate fluid-water. Therefore, the equations below are solved twice for both the sodium tube and the water tube.

$$\Delta Q = UA\Delta T \tag{1}$$

$$U = \frac{1}{\frac{1}{h_s}+\frac{1}{h_{F,s}}+\frac{d_o}{2k}ln\left(\frac{d_o}{d_i}\right)+\frac{d_o}{d_i}\frac{1}{h_{F,t}}+\frac{d_o}{d_i}\frac{1}{h_t}} \tag{2}$$

$$A = \pi d_o L \tag{3}$$

$$\Delta T = \frac{(T_{1,i+1}-T_{2,i+1})-(T_{1,i}-T_{2,i})}{ln\left(\frac{(T_{1,i+1}-T_{2,i+1})}{T_{1,i}-T_{2,i}}\right)} \tag{4}$$

The overall heat transfer coefficient is calculated as equation (2) with the heat transfer coefficient for each fluid obtained from the heat transfer correlation in Table I. Subscripts *s* and *t* indicate the shell and tube, and h_F is the heat transfer coefficient by a fouling effect. The heat transfer area is calculated based on the outer diameter of the tube, and the temperature difference between the two fluids is obtained using the logarithmic mean temperature difference.

The heat transfer rate changes the enthalpy of each fluid by the energy balance equation. The energy balance equations for each fluid are as follows.

$$\bar{h}_{s,i+1} - \bar{h}_{s,i} = \frac{\Delta Q_s}{w_s} \tag{5}$$

$$\bar{h}_{i,i+1} - \bar{h}_{i,i} = \begin{cases} \frac{\Delta Q_s - \Delta Q_w}{w_i} & ; upward\ flow \\ \frac{\Delta Q_w - \Delta Q_s}{w_i} & ; downward\ flow \end{cases} \tag{6}$$

$$\bar{h}_{w,i+1} - \bar{h}_{w,i} = \frac{\Delta Q_w}{w_w} \tag{7}$$

The enthalpy of the sodium and water are increased by the values of heat transfer rate divided by the mass flow rate, respectively. The enthalpy change of the intermediate fluid is expressed by equation (6) according to the flow direction.

The total pressure drop is as follows.

$$\Delta P_{tot} = \Delta P_{fric} + \Delta P_{acc} + \Delta P_{grav} \tag{8}$$

The frictional pressure drop is as follows, and the friction factors are obtained from the pressure drop correlation in Table I.

$$\Delta P_{fric} = f\frac{L}{d}\frac{\rho u^2}{2} \tag{9}$$

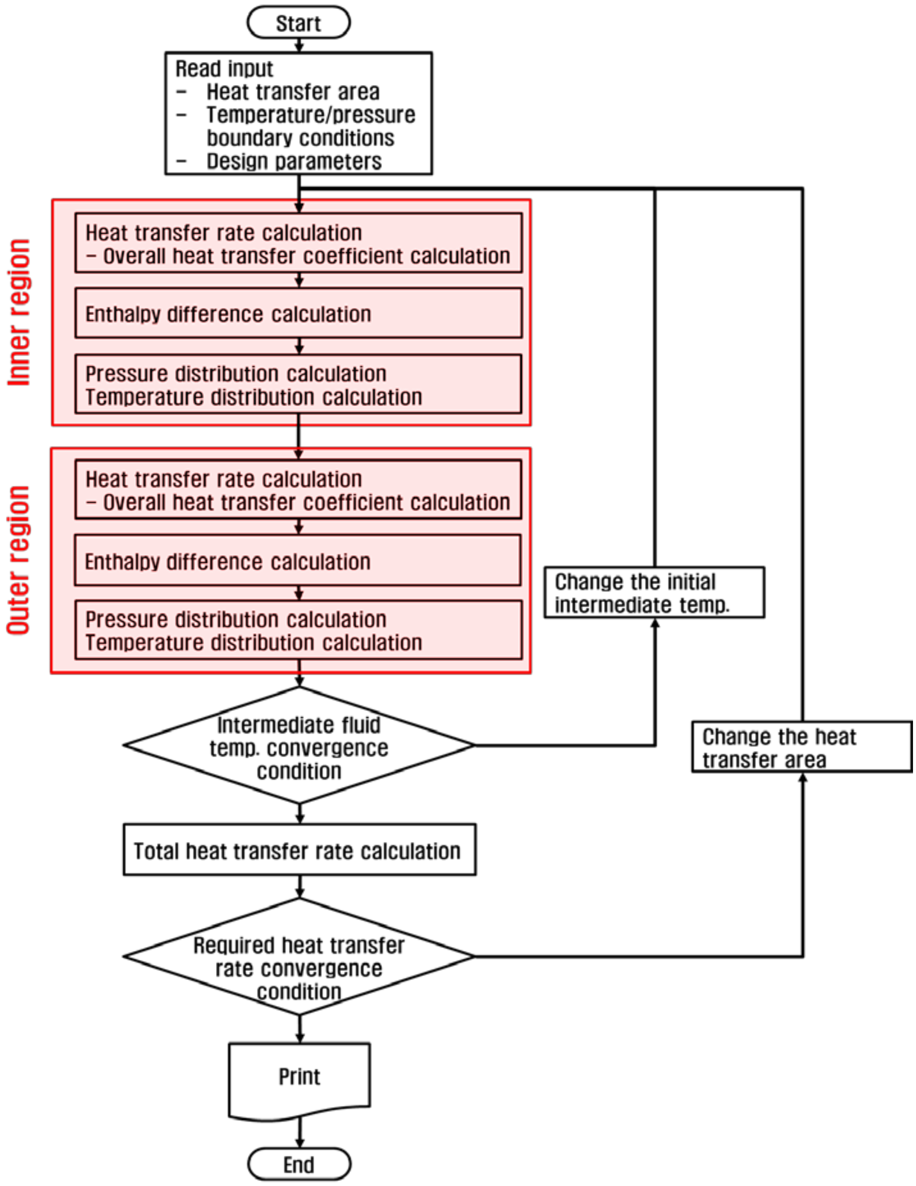

Fig. 3. Flow chart of SPINS-H

The calculation of SPINS-H follows the flow chart of Fig. 3. At first, the calculation is performed by taking the heat transfer area, temperature/pressure boundary conditions, and design parameters as inputs. The procedures for the inner and outer regions are carried out in the same way in the code. The heat transfer rate and the enthalpy change are calculated through equations (1) through (4) and equations (5) through (7). After calculating the pressure distribution through equations (8) and (9), the temperature distribution is calculated by the given enthalpy and pressure. After the calculations for both regions are completed, it is checked that the temperatures of the intermediate fluid at the two ends, top and bottom, are the same. If not, the procedures are iterated by changing the input value of the intermediate fluid temperature. If the convergence condition of the intermediate fluid is satisfied, the total heat transfer rate is compared with the required heat transfer rate. If there is a difference between the two values, the iterative calculation is performed from the beginning by changing the heat transfer tube length. If the values are equal, they are printed out and the calculation is finished.

Table I: Heat transfer and pressure drop correlations

Heat transfer correlations	
Sodium	Lyon-Martinelli
Lead-bismuth	Kalish-Dwyer
Water, single-phase	Mori-Nakayama
Water, two-phase	Chen
Pressure drop correlations	
Sodium	Mori-Nakayama
Lead-bismuth	Gunter-Shaw
Water, single-phase	Mori-Nakayama
Water, two-phase	Homogeneous equilibrium model

4. Result

An example of the analysis result calculated by SPINS-H is shown in Table II. The analysis is conducted for KALIMER-600. The sodium inlet temperature and the water outlet temperatures are constant values as boundary conditions. The number of tubes are determined by the arrangement rule mentioned above. The heat transfer rate and the tube inclined angle are given values as input, and the other values, not mentioned above, are calculated output by SPINS-H.

Table II: Analysis result of H-ICSG

Number of units	4
Heat transfer rate [MW_{th}]	387
Sodium inlet temp. [C] (inner/outer)	510 / 510
Sodium outlet temp. [C] (inner/outer)	356 / 374
Water inlet temp. [C] (inner/outer)	217 / 217
Water outlet temp. [C] (inner/outer)	459 / 481
Intermediate fluid temp. [C] (top/bottom)	497 / 327
Number of sodium tubes (inner/outer)	921 / 996
Number of water tubes (inner/outer)	875 / 1096
Total tube length [m]	27.4
Tube inclined angle [deg]	15
Diameter of shell [m]	6.4
Height of tube bundle [m]	7.1
Total heat transfer area [m^2]	9118
Heat flux [kW/m2]	42.4
Total pumping power [kW]	208.5

5. Conclusion

A one-dimensional analysis code for the H-ICSG, SPINS-H, was developed. This code is aimed at analyzing the thermal sizing and performance of an integrated steam generator using a three-fluid system.

SPINS-H performs a one-dimensional calculation along the vertical direction of H-ICSG. Based on the heat transfer calculation of a shell-and-tube heat exchanger, the heat transfer model among three-fluid was made, and the temperature and pressure distribution of each fluid can be obtained from the model. In the SPINS-H, it is possible to calculate the heat transfer length corresponding to the target heat transfer rate by iterating the calculation at a given heat transfer length.

SPINS-H will be used for the performance evaluation and the optimization of design parameters for H-ICSG, and will be the basis of one-dimensional analysis codes for new types of ICSG.

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Nomenclature

A	heat transfer area
d	tube diameter
f	friction factor
h	heat transfer coefficient
$\bar{h}$	enthalpy
k	thermal conductivity
L	tube length
P	pressure
Q	heat transfer rate
T	temperature
U	overall heat transfer coefficient
u	velocity
w	mass flow rate

Greek letters

ρ	density

Subscripts

acc	acceleration
F	fouling
fric	frictional
grav	gravitational
i	inner, intermediate, node number
o	outer
s	shell, sodium
t	tube
w	water

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