

Three-dimensional Analysis of Thermal-Hydraulic Characteristics on an Integrated Steam Generator with Serpentine Tube Bundles

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1. Introduction

A sodium-cooled fast reactor (SFR) has been considered one of the most promising options to meet the requirements of a Gen-IV system. An SFR can have enhanced safety features by using liquid sodium as a coolant; however, there is concern regarding unexpected events coming from a sodium-water reaction (SWR) in a steam generator unit. So, an IHX-Combined Steam Generator (ICSG) was proposed as a concept which have an intermediate fluid filled in the shell-side, replacing the intermediate heat transfer system (IHTS) of a sodium-cooled fast reactor (SFR). The intermediate fluid make heat transfer from the sodium to water as well as significantly reducing the risk of SWR, and it means improvement of both cost-effectiveness and safety [1-3].

In the previous research, we have proposed a novel serpentine tube type ICSG (S-ICSG), which has a 12-pass serpentine tube configuration that is strong at modularity and easy to ensure a certain flow rate of the intermediate fluid [4]. We also have developed a one-dimensional computer code to conduct thermal-sizing and thermal-hydraulic evaluation for S-ICSG (SPINS-S, Sizing and Performance Analyzer for an Integrated Steam Generator – Serpentine tube arrangement) [4]. However, the SPINS-S code should be verified by an independent evaluation method such as analysis using a conventional CFD tool and compared the results. In addition, a 3-D analysis can evaluate complex thermal-hydraulic characteristics that cannot be confirmed by SPINS-S. In this study, three-dimensional analysis using the commercial CFD program (ANSYS CFX) was performed on the S-ICSG which is previously designed by SPINS-S, and the thermal-hydraulic characteristics were evaluated more specifically.

2. Methods

2.1 Design and modeling of S-ICSG

The S-ICSG is a novel steam generator concept that can solve the difficulty of pumping of the intermediate fluid and easy to modularize. It consists of two units, the upward-region and the downward-region unit as a flow direction of the intermediate fluid. Fig. 1 shows a concept drawing of an S-ICSG. Sodium flows from the

upper chamber to the lower chamber, and water flows from the lower chamber to the upper chamber, changing the steam with both a high temperature and a high pressure. The Lead-Bismuth Eutectic (LBE) used as the intermediate heat transfer fluid is in a steady state condition by circulating between two units as represented in Fig. 1.

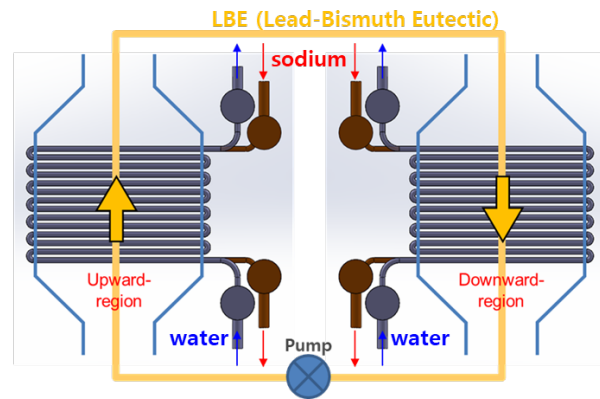


Fig. 1. Schematic drawing of the S-ICSG concept.

Sodium and water tubes are alternately arranged in the same number of tubes adjacent to each other. The bending parts of the tubes and the chambers are located away from the main flow path of the intermediate fluid. There is a flow-guide wall installed with many penetrations, but a pressure boundary with the atmosphere is the outermost wall of S-ICSG units. Fig. 2 represents the 3-D modeling result of the designed S-ICSG.

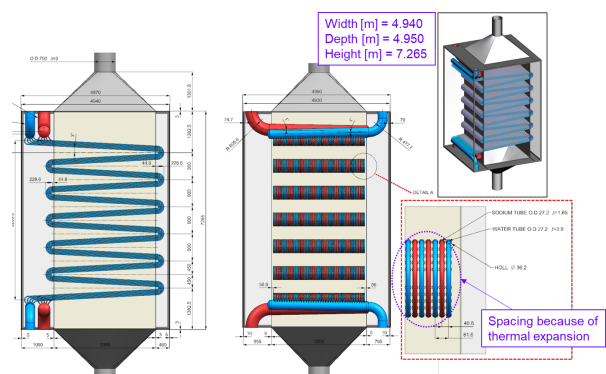


Fig. 2. Three-dimensional modeling result of the S-ICSG unit.

2.2 Mesh Generation and analysis conditions

As a result of preliminary evaluation of the number of meshes, it was impossible to conduct the entire model analysis we have. So, the analysis was simplified by adaption of a periodic model containing one sodium tube and one water/steam tube as shown in Fig. 3.

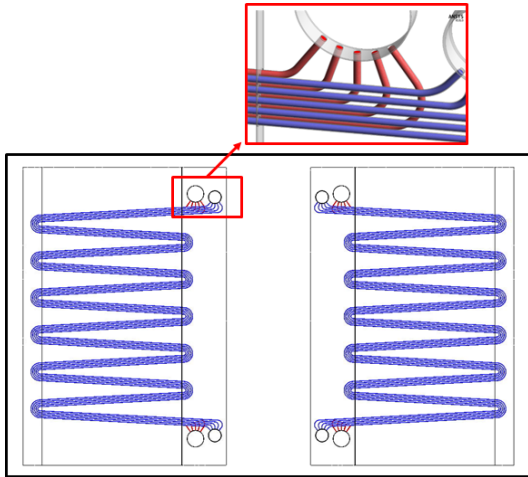


Fig. 3. Periodic model for analysis with the realistic mesh generation.

The LBE inlet and outlet were considered as square boxes, and the inlet and outlet of the fluid region in each tube was defined as the connection parts between the chambers and the tubes. The internal flow of the chamber was excluded from the analysis part. All solid structures that could affect the analysis were implemented, and the outermost surface was considered as insulation conditions. In the mesh generation, the sweep mesh was applied to each tube and the inner flow field of the tube, and the chamber and the tube were composed of two mesh layers across the tube wall. As a result, a total of 170 million elements were generated as shown in Fig. 4.

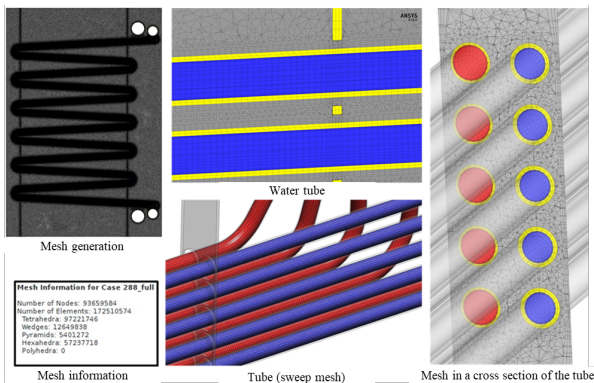


Fig. 4. Mesh generation results.

The material properties of 9Cr-1Mo were used for the tubes and chambers, and additional contact thermal resistance was considered at the inner surface of the water tube for the fouling effect.

The physical properties of all fluids used in the analysis were taken into account for changes in temperature. In order to analyze the phase change of water, the equilibrium phase change model was applied with consideration as a homogeneous binary mixture implemented in ANSYS CFX IAPWS table. The shear stress transport (SST) model was used as the turbulent model for all fluid.

3. Results and Discussion

3.1 Thermal behaviors

In the S-ICSG unit, heat is transferred from the hot sodium to the cold water through the LBE by dominant local heat transfer phenomena. Fig. 5 shows the temperature distribution of the vertical cross section of the sodium tube center. The hot sodium (510°C) was divided into the upward- and downward-region units, and it gradually loses heat. The sodium outlet temperature of the downward-region is 20°C higher than those of the upward-region. The temperature distribution of the water/steam tube shows that the downward-region has a wider distribution of higher temperature zones, and the outlet temperature of the steam in the downward-region is 15°C higher as shown in Fig. 6. Since the LBE circulates between both units, the inlet and outlet temperatures of each unit have the same value, but it can be observed that the hot zone is distributed more widely in the downward-region as shown in Fig. 7. This is because the LBE stays in the hot part for a relatively long time in the downward-region due to the natural-draft effect to the opposite direction with the forced-draft flow.

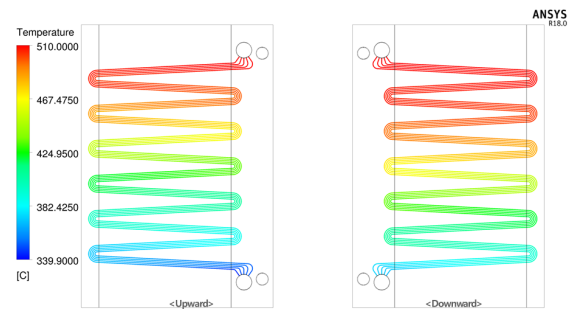


Fig. 5. Temperature distribution of sodium tubes.

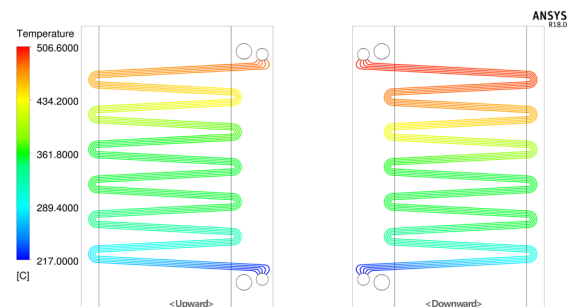


Fig. 6. Temperature distribution of water/steam tubes.

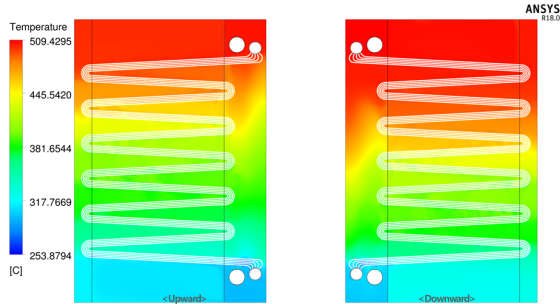


Fig. 7. Temperature distribution of LBE.

Because of this heat transfer characteristic, a part where the phase change occurs completely is located former in the downward-region as represented in Fig. 8.

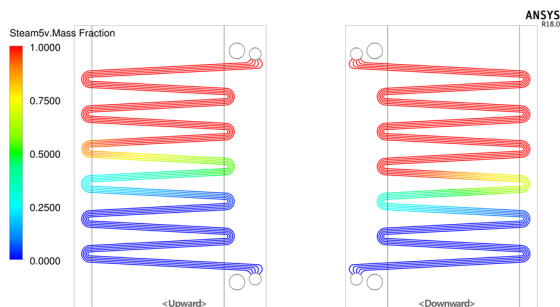


Fig. 8. Mass fraction of water/steam tubes.

3.2 Fluidic characteristics

Fig. 9 shows the absolute pressure inside the water/steam tubes. More vapor expansion pressure occurs in the downward-region, which results in higher pressures.

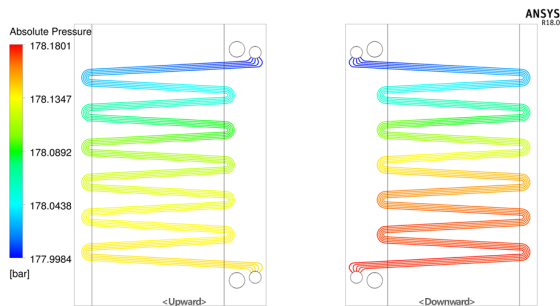


Fig. 9. Absolute pressure inside water/steam tube.

The velocity vector results of the LBE show that some part of LBE flows through the gap in the flow guide wall, and local flow patterns can be observed in the flow stagnation region where the bending parts and the chambers are located (Fig. 10). Because of the very slow flow velocity of LBE, some regions are affected by natural convection, resulting in irregular flow patterns. Therefore, it might require specific evaluation about the natural convection effect in the view of the steam generator performance.

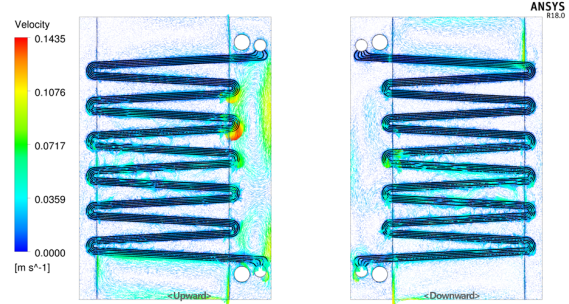


Fig. 10. Velocity vectors of LBE.

3.3 Comparison with SPINS-S

We compared the CFD results with SPINS-S results as shown in Table I. The results represent very good agreement with the differences below 5%.

Table I: Comparison results with SPINS-S

	Region	CFD (°C)	SPINS-S (°C)	Diff. (%)
T _{out} (Sodium)	UP	350.5	359.2	-2.48
	DOWN	371.2	371.5	-0.08
T _{out} (Steam)	UP	484.3	463.6	4.27
	DOWN	499.8	481.5	3.66
T _{top} (LBE)	UP	501.3	494.5	1.36
	DOWN	501.3	494.5	1.36
T _{bottom} (LBE)	UP	320.6	333.1	-3.90
	DOWN	320.6	332.9	-3.84

4. Conclusions

The three-dimensional computational analysis using commercial CFD software was carried out on the designed S-ICSG. Through this study, local flow patterns, which are difficult to be observed in the one-dimensional analysis using the design code, were identified. The analysis results can be used to reduce the uncertainty of the designed S-ICSG performance and the gap between the design and the real component.

ACKNOWLEDGMENTS

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