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Stress Analysis of an IHX-Combined Steam Generator with Serpentine Tube Bundles

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1. Introduction

A sodium-cooled fast reactor (SFR) can have inherently enhanced safety features by using liquid sodium as a coolant; however, there is concern regarding unexpected events coming from a sodium-water reaction (SWR), especially in a steam generator unit. To overcome this problem, an IHX-Combined Steam Generator (ICSG) was proposed. It has 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 [1,2].

In the previous research, we have proposed and designed a 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 [3]. We also carried out thermal-hydraulic performance evaluations using both the design code and a conventional CFD tool [4], but there was very little consideration in the view of a structural design and evaluation. In this study, the three-dimensional structural integrity evaluation using the commercial FE analysis program (ANSYS v17.2) was performed on the previously designed S-ICSG.

2. Methods and Results

2.1 Modeling and mesh generation

The S-ICSG consists of two units with opposite flow directions of the intermediate fluid. Sodium flows downward, and water flows upward, changing the steam. The Lead-Bismuth Eutectic (LBE) as the intermediate heat transfer fluid circulates between two units as shown in Fig. 1.

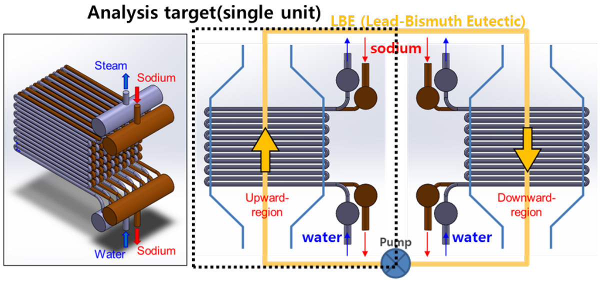

Fig. 1. Concept drawing of the S-ICSG.

To conduct the stress analysis, the outer shell and supports were designed additionally. Fig. 2 shows FE (Finite-Element) models for the target S-ICSG unit by using ANSYS 3D elements (SOLID70 and SOLID185). The S-ICSG has 380 tubes in a unit, but it is very heavy to generate the model including whole tubes. So only one pair (one sodium tube and one water/steam tube) of tubes was modeled for this stress analysis. The total number of nodes was 291,371 and the total number of elements was 263,792. Material properties for Mod.9Cr1Mo(T91) were obtained from RCC-MRx Section III, Tome 1, Subsection Z [5].

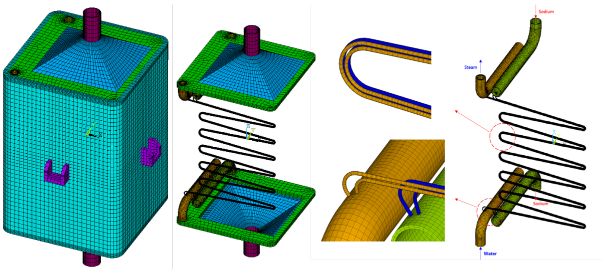

Fig. 2. FE modeling and mesh generation for stress analysis.

2.2 Boundary condition

Thermal boundary conditions were adapted using the previous analysis results of thermal-hydraulics on the steady-state condition [4]. In general, the stresses caused by mechanical loads (dead weight and pressure) including head pressure are mostly primary stresses, and the stresses generated by thermal loads are classified as secondary stresses. Primary loads considered were the dead weights of fluid and gravitational acceleration. Major factors of pressure boundary conditions for tube inside was the operating pressure, but the head pressure was crucial in the interface adjacent to the shell-side LBE. Degree of freedom for mechanical loads were applied to allow the thermal expansion in the horizontal plane. Fig. 3 shows the mechanical constraints at the support locations and pressure boundary conditions by the primary loads. A total of 100 operating cycles and a holding time of 2,400 hours per a cycle are assumed for thermal loads.

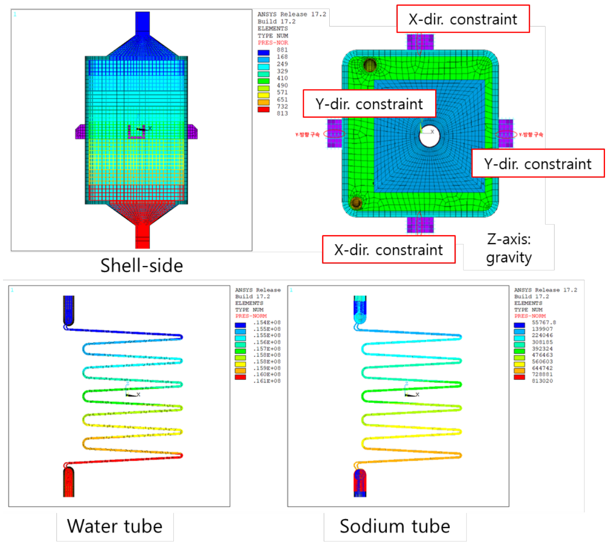

Fig. 3. Constraints and pressure boundary conditions.

2.3 Stress analysis result

We obtained primary stresses (due to dead weight and pressure loads) and secondary stresses (due to thermal loads) using ANSYS. Fig. 4 shows the stress distributions from the stress analysis under primary loads. The maximum stress was about 136 MPa at the welded part of the lower cone shape. The thermal stress analysis was performed by applying the temperature obtained from the steady-state thermal-fluidic analysis with appropriate convective heat transfer coefficients. The maximum stress under secondary loads was about 224 MPa in the welded part between the sodium chamber and the bottom plate as shown in Fig. 5.

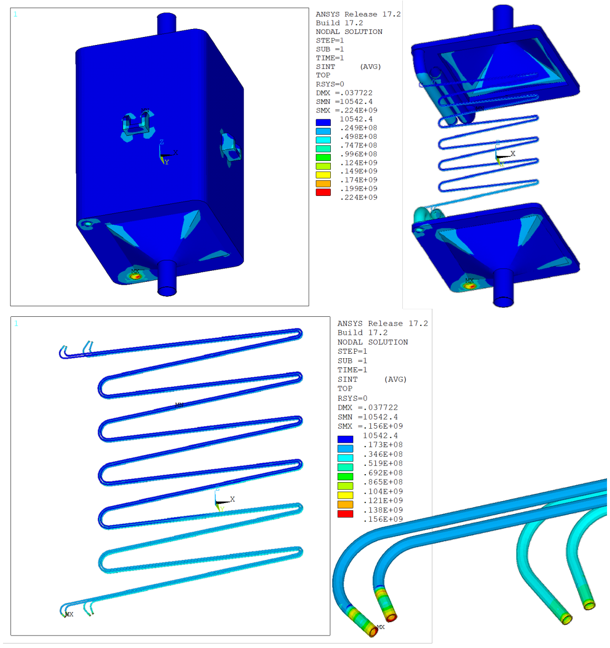

Fig. 4. Stress analysis results under primary loads.

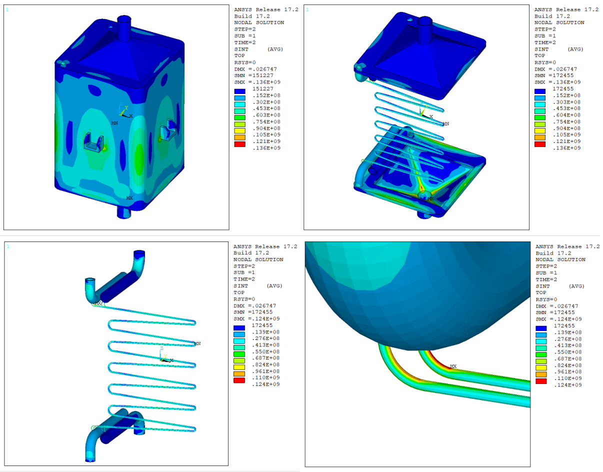

Fig. 5. Stress analysis results under secondary loads.

3. Conclusions

Thermal and stress analyses of the newly developed S-ICSG were performed using a commercial finite element analysis program. For this, 3D finite element analyses with FE model with outermost shell and support, and the boundary conditions based on the results of the previous thermal-hydraulic analysis were performed. The maximum stress intensities of the primary and secondary stresses were about 136 MPa and about 224 MPa, respectively, which shows relatively high level of primary stresses with reasonable level of secondary stresses. Based on the analysis results, stress linearization and integrity evaluations according to the RCC-MRx will be performed as future works.

ACKNOWLEDGMENTS

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[5] Afcen RCC-MRx Code, Section Ⅲ, Tome 1, Subsection Z, Appendix A3.18AS, 2015 edition.