Integrated Fluid-Structure Modeling and Analysis of a Long-cycle SFR Using Open-source Codes

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1. Introduction

The evaluation of structural integrity through thermomechanical loading analysis is critical in the design of high-temperature operating reactors such as SFRs. Thermofluid-structure coupled analysis is required to verify the structural integrity of the reactor under normal and transient operation conditions, and multidimensional detailed analysis can improve the analysis's reliability over one-dimensional system analysis. A detailed analysis model that includes both the reactor and the heat transfer system is being developed for SALUS, a long cycle SFR reactor. A three-dimensional fluid-structure integration analysis is used to model the primary heat transfer system (PHTS), and a system analysis code is used to model the intermediate heat transfer system (IHTS) and the decay heat removal system (DHRS).

This paper describes the PHTS's integrated analysis methodology and modeling. For flow and structural analysis, open source codes are used, and an open source library is used to connect the two models. The thermofluid analysis including the solid region is performed using OpenFOAM's multi-domain conjugate heat transfer solver [1], and the temperature information of the fluid-solid interface boundary is passed to the structural analysis solver to perform the stress analysis. The PHTS and subsystems of the SALUS reactor were modeled in this paper, and the hot and cold pool temperatures at rated operation were evaluated, as well as the thermos-structural safety of the structure.

2. Simulation Models

2.1 SALUS reactor design

The Small, Advanced, Long-cycled, and Ultimate Safe SFR (SALUS) is a long-cycle sodium-cooled fast reactor with a capacity of 100 Mwe. The core's rated thermal power is 267 MWt, its inlet and outlet temperatures are 360°C and 510°C, respectively, and the flow rate through the core is 1365.7 kg/s [2]. Four intermediate heat exchangers (IHX) are installed between the hot sodium pool and the cold sodium pool, with each unit capable of removing 66.37 MWt of heat. Four decay heat exchangers (DHX) of the DHRS with a design heat removal capacity of 1.67 MWt per unit are installed in the low-temperature sodium pool to remove decay heat in the event of a design basis accident.

The upper section of the core is outfitted with an Upper Internal Structure (UIS), which includes a system for inserting and removing instrument bundles and control rods. A heat shield made up of several thin plates is installed between the argon gas region above the sodium pool and the reactor head to protect it from the high heat of the sodium pool.

The Reactor Vessel (RV) and the reactor head enclose the sodium pool and the argon area, and a Containment Vessel (CV) surrounds the RV in case of sodium leakage from the RV, and nitrogen gas is filled between the two vessels. The Reactor Vault Cooling System (RVCS) is installed outside the CV to remove heat from the CV through natural convection, and an air chimney is constructed at the top of the air flow path to create a natural development head. The Head Access Area (HAA), which is located in the upper part of the reactor head, will have ducts for inlet and outlet air to cool the reactor head.

The analysis includes fluid flow regions such as reactor sodium pool, argon gas area, nitrogen gas area, cooling areas by air and solid regions such as reactor vessel, containment vessel, reactor head, skirt, reactor internal structure. Figure 1 depicts the layout and geometry of the SALUS reactor's PHTS components.

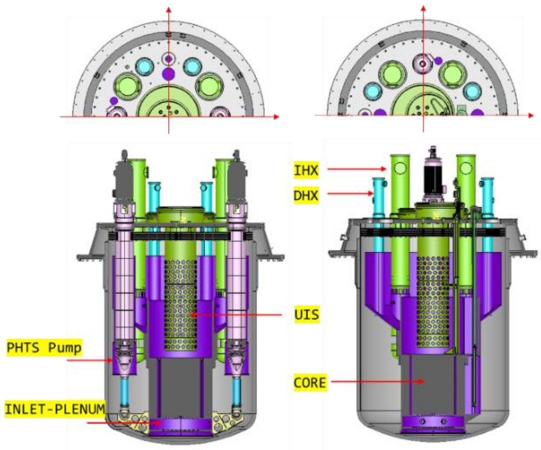

Fig.1 SALUS layout

2.2 Grid generation and modeling

The Salome program [3] was used to perform geometry simplification on the SALUS reactor's three-dimensional CAD geometry. We attempted to generate as many hexahedron meshes as possible when generating the mesh because using a hexahedral mesh rather than a tetrahedral mesh for thin structures such as RV and CV, boundary layer regions near walls, and so on can provide various numerical and computational benefits such as reducing numerical errors and improving convergence while reducing the number of meshes.

The hexahedral mesh was generated using Salome's 'SMESH' module, and in areas where generating a hexahedral mesh was difficult due to complex geometry, the 'snappyHexMesh' program, an OpenFOAM mesh generation utility program, was used. The program requires a background mesh for the area to be meshed, and the background mesh was created using Salome or the utility program 'blockMesh.' The analysis areas are divided into regions suitable for meshing, and each mesh is generated for each region before being stitched together using the utility program 'stitchMesh.' In the case of symmetry, the utility program 'mirrorMesh' was used to generate the opposite grid.

The complex structure was modeled as a porous medium and a conjugate heat transfer boundary condition was applied at the fluid-structure interface. Figure 2 depicts the areas modeled as porous media: nuclear fuel assembly, assembly orifice, inlet plenum, IHX, DHX, UIS, and pump impeller.

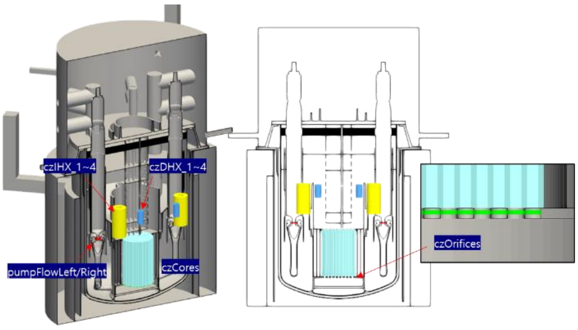

Fig. 2 Porous media regions

A pressure loss model is applied to the porous medium, and heat sources and sinks for the nuclear fuel assembly and heat exchanger, respectively, are provided, as well as velocity information for the pump impeller region. In the future, pressure losses by flow group will be applied to the assembly orifices, and additional detailed models will be applied to the heat source by nuclear fuel location. Representative grid systems of the sodium pool area, argon area, HAA, and RVCS are shown in Figures 3 and 4. The solid structures inside the reactor include the redan, core shield, inlet plenum, and supports. The exterior consists of the reactor vessel, containment vessel, reactor head, and skirt. Figure 5 depicts the grid systems of the internal and external structures.

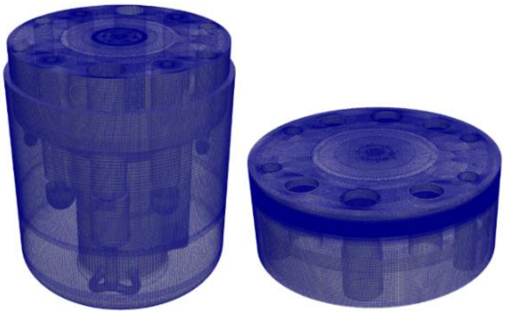

Fig. 3. Grid systems for the sodium pool (left) and the argon area (right)

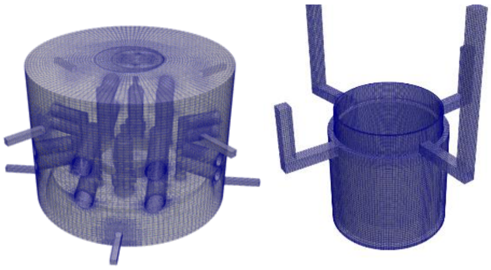

Fig 4. Grid systems for the HAA (left) and the RVCS (right)

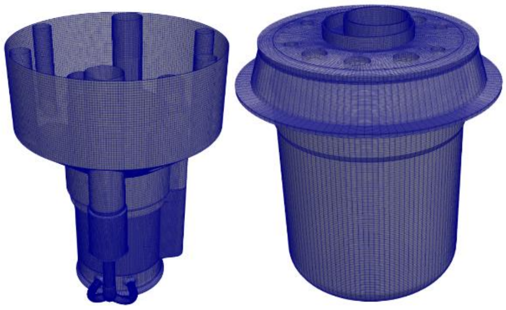

Fig 5. Grid systems of the inner (left) and the outer (right) region of the reactor

2.3 Fluid and solid analysis solvers

OpenFOAM's fluid and solid solvers were employed. For conjugate heat transfer analysis, 'chtMultiRegion Foam' was used, and for structural stress analysis, 'solid DisplacementFoam' was used. This structural analysis solver was created using the finite volume method, which differs slightly from the existing codes created using the finite element method, but according to the reference [4], the structural analysis using the finite volume method can produce results comparable to the analysis created using the finite element method.

The advantage of using an OpenFOAM-based structural analysis solver is that it is simple to generate element-independent meshes for structures with complex geometries, and it is simple to extract the thickness-direction stress data required for stress linearization in ASME-based structural integrity assessment. However, considering the structure's self-weight or adding hydrostatic pressure of the fluid or pressure on the flange connected by other structures in 'solidDisplacement Foam' is difficult. As a result, the structural analysis solver was modified to account for the structure's self-weight, hydrostatic pressure as a function of height, and additional pressure.

The SALUS simulation model examines 18 regions: 5 fluid and 13 solid. For areas such as argon, nitrogen, HAA, and RVCS flows, radiation heat transfer is considered, and insulation conditions are imposed on pump and heat exchanger shrouds that do not reflect solid structures. Because the pipes connecting to the heat exchanger in the HAA are insulated, this was taken into account, and an adiabatic condition was imposed on these boundaries. Air at 20°C is forced in through four inlet ducts installed on the top of HAA, and the air volume is set to a total of 4.73 m^3/s, but this needs to be adjusted further through evaluation. The current RVCS model can simulate natural convection, but because it is a steady-state analysis, the design air flow rate of 40°C and 4.96 kg/s was given to accelerate convergence.

Because the current solver-to-solver information transfer library, 'preCICE' [5] can only transfer one region from a multi-region solver, the grids for the reactor head, skirt, reactor vessel, and containment vessel are stitched together and named 'STRUCTURE,' and the boundary temperature information is transferred to the structural analysis solver. As shown in Figure 6, after analyzing heat flow and conjugate heat transfer for multiple regions of SALUS, the boundary surface information is transferred to the 'STRUCTURE' region using preCICE and stress analysis is performed.

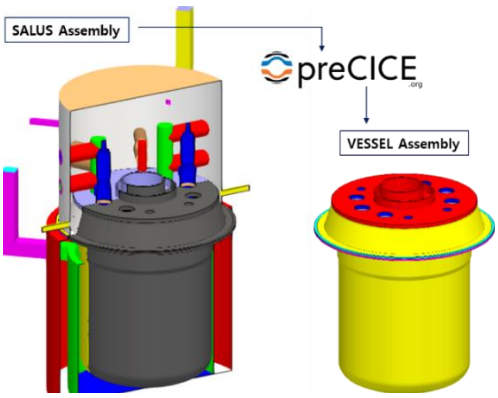

Fig. 6. SALUS coupled analysis model

3. Results

3.1 Fluid flow

As shown in Figure 7, the heat generated by the nuclear fuel assembly causes high temperatures in the structure in contact with the redan and hot pool. Lower temperatures can be found in the cold pool beneath the redan as well as the upper argon gas region. Temperatures outside the containment and above the reactor head are kept low by forced or natural air cooling.

Figure 8 depicts the sodium temperature and velocity distributions, as well as the basic circulating heat flow phenomenon caused by the pumps. The highest temperature zone forms at the core's outlet, and there is also a high temperature zone at the bottom of the UIS. The heat is transferred from the hot pool to the cold pool via convection → conduction → convection through the redan. The velocity distribution shows that the temperature is kept relatively high as hot sodium is ejected from the core outlet via the control rod driving tube into the UIS area between the second and third support plates.

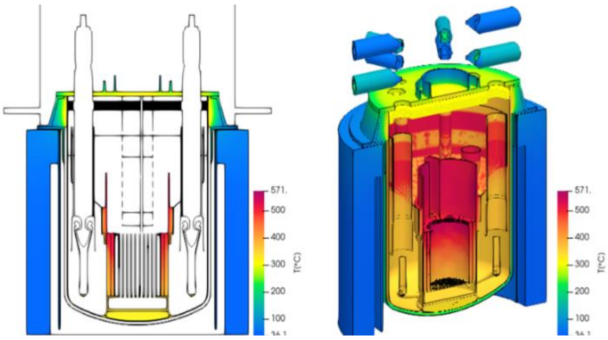

Fig.7. Structure temperature distribution

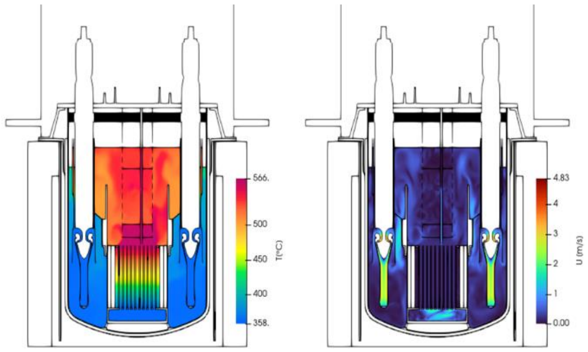

Fig. 8. Sodium temperature (left) and velocity (right) distributions at a cross section

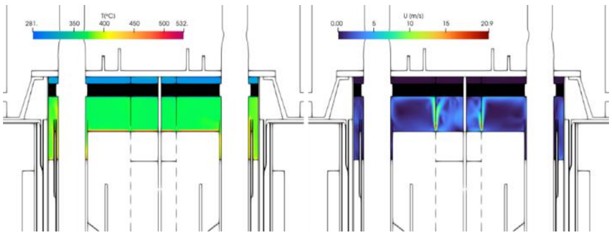

Fig. 9. Gas temperature (left) and velocity (right) distributions at a cross section

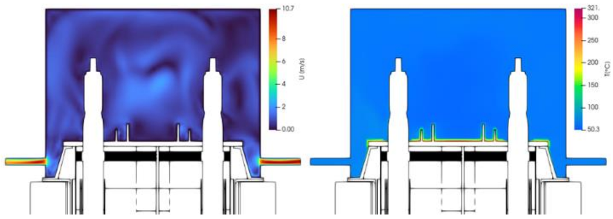

Fig. 10. Air velocity (left) and temperature (right) distributions at a cross section for the HAA region.

As illustrated in Figure 9, the heat shield protects the reactor head by preventing radiation and convective heat transfer from the free surface of the hot sodium pool.

The air flow injected from the HAA region cools the heat released from the reactor interior through the reactor head. If further reactor head temperature reduction is required, the current airflow should be modified and evaluated. Figure 10 shows how the air injected from the top descends from the center of the zone to cool the exposed components, then turns horizontal to cool the reactor head before exiting through the outlet.

Figure 11 depicts the RVCS results with natural convection air heat removal from the containment's outer wall. There is a localized strong flow in the lower part of the containment vessel, which may cause issues with the one-dimensional design code.

The average temperature of the hot pool and cold pool sodium is calculated to be 509.17°C and 357.64°C, respectively, with 0.16% and 0.66% error from the design value. The heat loss to the RVCS is computed to be 0.10973 MW, while the heat loss to the HAA is computed to be 0.16492 MW. After the design values have been finalized, these can be compared.

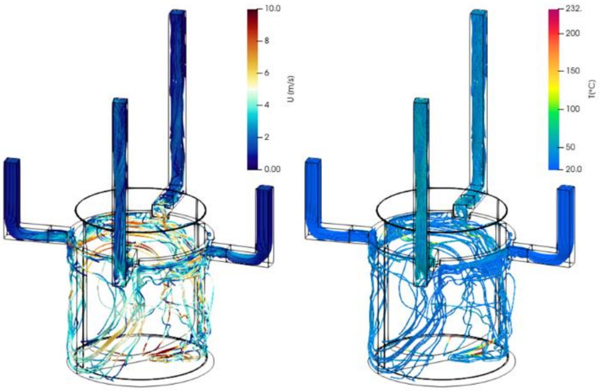

Fig. 11. Air velocity (left) and temperature (right) distributions along the streamlines in the RVCS region.

The stress distribution is depicted in Figure 12. Overall, the distribution of stresses is consistent with the vessel's and head structure's integrity, but stresses are concentrated in the skirt area. The current structural analysis solver is incapable of separating the reactor head, skirt, and containment vessel and applying a 'contact' boundary condition at the interfaces. As a result, the current results are the result of a failure to impose precise boundary conditions where the skirt connects to other structures. It is expected that applying the 'contact' boundary using 'solids4Foam' [6] in the future will provide improved results that reflect actual conditions.

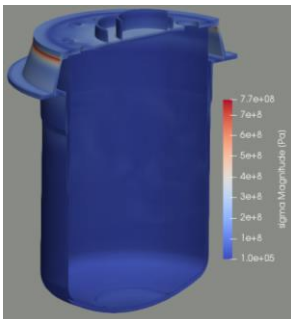

Fig. 12 Preliminary stress distribution.

4. Conclusion

The SALUS reactor is made up of several domains, including sodium, argon, nitrogen, and air fluid domains and solid domains of various materials. Using OpenFOAM's thermo-fluid analysis solver, structural analysis solver, and preCICE coupling library, we created an analysis system capable of performing fluid-structure coupled analysis.

The steady-state analysis resulted in the design thermal equilibrium being satisfied. To reduce computational load during transients, the grid system was generated as much as possible with a hexahedral mesh, and the component with complex geometry was modeled as a porous medium. Structural integrity for SALUS was evaluated using fluid-structure coupled analysis, and additional improvements to the structural analysis model were identified. Following the integration of the system analysis code, the entire reactor's design and safety will be evaluated.

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