Assessment of reactor integrity and operational conditions with open source software

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1. Introduction

The complex heat transfer and three-dimensional thermal fluid behavior inside the reactor must be linked to a secondary system that influences the reactor pool's thermal state in order to assess the structural integrity of the reactor and determine the linked system's operating parameters. In order to achieve this, the secondary system's thermal flow analysis code was connected with a three-dimensional analysis code that calculates heat flow and conjugate heat transfer inside the reactor [1].

The connectivity methodology is undergoing modifications and additions. This research assesses the validity of this coupling method by using it for the linked system's operating conditions and the reactor structure's integrity examination. The coupled analysis approach was applied to SALUS, a long-period SFR reactor [1]. The structure's integrity is assessed under mechanical load and heat in accordance with the reactor sodium pool's temperature variations. Evaluations were also conducted on the design performance of the reactor vault cooling system (RVCS) [2], which cools down the containment vessel's outside.

2. Coupled analysis approach

2.1 Introduction of a coupled analysis model

The coupled analysis consists of two parts: linking the 3D thermal fluid flow analysis code with a structural analysis code, and linking the 3D thermal fluid flow analysis code with the one-dimensional system analysis which solve secondary heat transport system. Applications of the three-dimensional heat flow analysis include the heat flow within the reactor vessel and the systems that are connected to it.

OpenFOAM's thermo-fluid analysis solver chtMulti RegionSimpleFoam [3, 4], GAMMA+ code for system analysis [5], structural analysis solver solid4Foam [6, 7], and coupling library preCICE [8] were utilized.

The three-dimensional code and the one-dimensional system code are connected at the heat exchangers DHXs and IHXs. The mass flow and heat transferred from GAMMA+ are processed as source terms in the momentum and energy equations in the OpenFOAM solver. The sodium temperature and pressure at the inlet and outlet of the heat exchanger shell side to be passed to the GAMMA+ code are averaged over the grids above and below the heat exchanger (HEX).

The mass flow rate from the GAMMA+ code is converted to the average flow velocity on the shell side of the heat exchanger, and the heat removal rate is converted to the heat loss per unit volume and processed into momentum and energy source terms through fvOptions, respectively.

2.2 Modification of the structural analysis solver

There is a radial clearance between the concrete supporting the reactor and the reactor skirt in high-temperature structures to prevent the creation of excessive thermal stress. It permits the structure to grow, and at the interface where the structures meet, a contact boundary forms. In the solidDisplacementFoam solver, there is no contact boundary condition model. Foam solver is an OpenFOAM solution for fundamental solid mechanics. solidDisplacementFoam solver is a basic solid mechanics solver of OpenFOAM. Therefore, solids4Foam [7] was applied to implement this boundary condition. Solids4Foam is a third-party program using the OpenFOAM library. In this study, it was compiled using the library of OpenFOAM-v9 version [9]. Furthermore, the original solids4Foam was adjusted to take hydrostatic pressure into account based on the coolant's liquid level. 'solidTractionBaric' is a model for solids4Foam that was developed to provide pressure in the form of hydrostatic pressure to the surface of the structure in contact with sodium based on the height from the liquid level.

In order to verify the added boundary condition, the punch problem was chosen among the examples provided by tutorials.

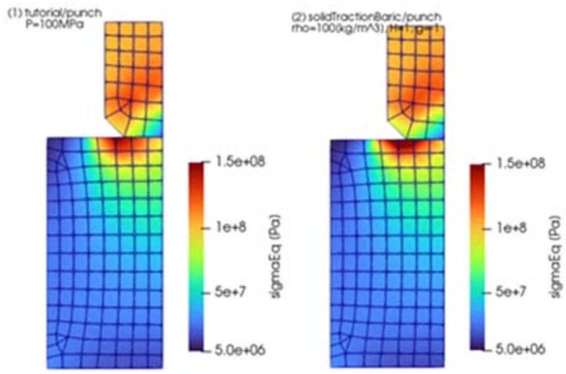

Fig. 1. Stress distributions by different boundary conditions (left: solidTraction, right: solidTractionBaric)

The upper surface of the upper structure is subjected to a 100 MPa load with the solidTraction boundary condition. By applying the solidTractionBaric boundary condition, an intentionally imagined density condition was applied, resulting in the same pressure as when a load of 100 MPa was applied. These settings were used for stress analysis, and the outcomes were compared to make sure they were the same. Fig. 1 compares the distribution of stress, and Fig. 2 displays the findings for vertical forces. The accuracy of the implementation of the hydrostatic pressure boundary condition was verified by analyzing the verification problem.

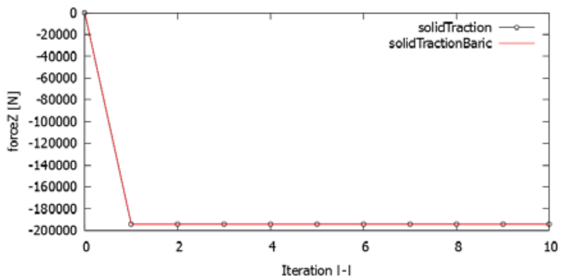

Fig. 2. Comparison of vertical force according to BCs

2.3 Procedure of the structural analysis

There are two approaches of analyzing a structure's thermal stress. One approach is to solve the conjugate heat transfer analysis and send the structure's boundary and internal temperature data to the structural analysis solver. The structural analysis solver can thus do stress analysis without having to solve the energy equation to obtain the temperature field. In order to find the interior temperature distribution, the alternative method entails passing the boundary temperature from the fluid solver to the solid solver and solving the energy equation. In the latter scenario, preCICE is utilized for data transfer and solidDisplacementFoam can be used as a solid solver.

The former should be used since the structural analysis solver solids4Foam does not solve the energy equation when the contact boundary condition is applied. However, preCICE only sends interface data, thus the new adapter needs to be developed to account for this. The boundary and internal temperatures of the structure are provided by the conjugate heat transfer analysis, therefore thermal stress analysis can be performed utilizing the temperature analysis results obtained without transferring temperature information via preCICE. The mapping of the temperature field is not necessary if the structure's grid for the conjugate heat transfer analysis and the structural analysis grid match. However, if a different grid system is being used, a mapping procedure is necessary to interpolate the conjugate heat transfer analysis's temperature data into the structural analysis grid.

The SALUS reactor's head, skirt, reactor vessel (RV), and containment vessel (CV) are among the structural analysis regions. The internal structural load given to the flange, the hydrostatic pressure of the sodium pool, and the weight of the structure were all taken into account. The containment vessel was mounted in a fixed condition on the concrete contact surface. Contact boundary conditions were added to the contact surface for the skirt and containment vessel. The structure was restrained from moving up-and-down on the upper skirt rim of the section.

For thermal stress analysis utilizing solids4Foam, structural temperature data following conjugate heat transfer analysis should be in the location indicated by "TcaseDirectory." A shell script was constructed to map the result file of the conjugate heat transfer analysis to a temperature file that will be created over time in "TcaseDirectory." The temperature field under normal operating condition is applied to the structure through mapping in Fig. 3.

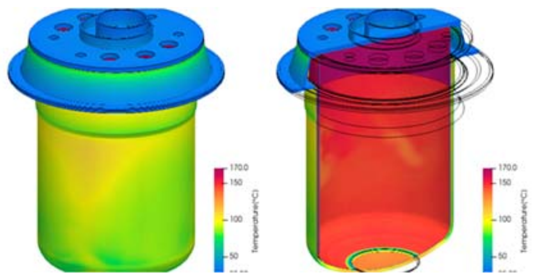

Fig. 3. Temperature field mapped to the structure for thermal stress analysis during normal operation

2.4 Stress analysis utilizing the preliminary calculation result of SALUS

From previous paper [1], preliminary calculations were performed from the steady state of the nominal operation to 300 s after the shutdown of the reactor. The sodium pool's temperature quickly decreased as every possible cooling method was considered. The average temperatures of the hot and cold pools vary, as seen in Fig. 4. The reactor's temperature distribution is depicted in Fig. 5.

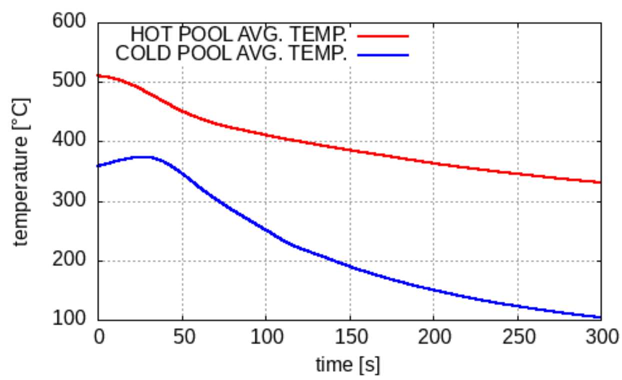

Fig. 4. Temperature variations from a coupled analysis of SALUS

Using the structure's temperature data from a coupled study, thermal stress during the transient period was examined. The stress due to hydrostatic pressure, self-weight, and thermal load is investigated from 0 to 360 seconds.

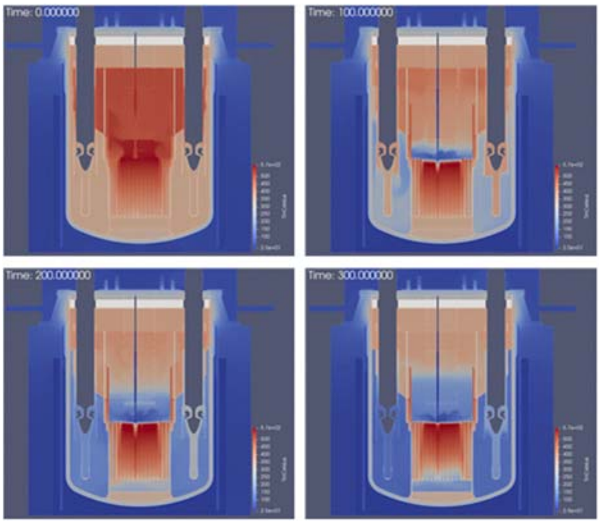

Fig. 5. Temperature fields from a coupled analysis of SALUS (from 0 s to 300 s)

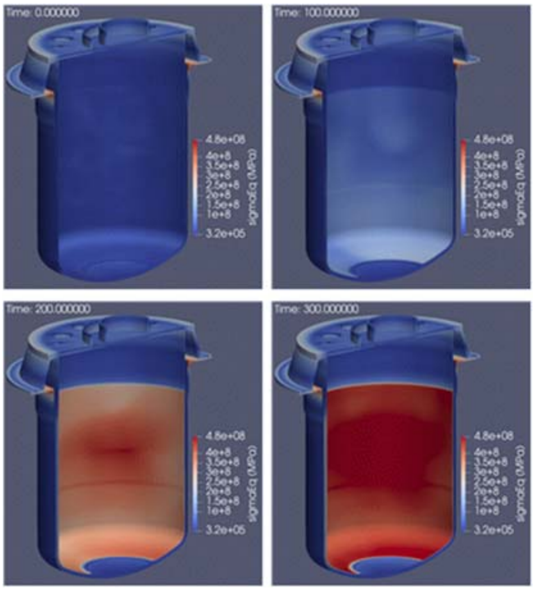

Fig. 6. Stress fields during transient of SALUS (from 0 s to 300 s)

The stress distribution throughout time is displayed in Fig. 6. It is the total stress, which includes the thermal stress brought on by the temperature differential as well as the stress brought on by the structure's own weight and hydrostatic pressure. As the transient grows, so does the stress within the reactor vessel. The current accident scenario is used to assess whether the coupled analysis is being carried out correctly; it is not a scenario taken into account in the safety analysis. The temperature difference between the inside and exterior rises as a result of the residual heat removal system's quick cooling of the interior and its relatively ineffective removal of heat from the exterior. This tends to significantly increase thermal stress.

2.5 Performance evaluation of the SALUS RVCS design

In the event of a serious accident, the RVCS of the SALUS is intended to remove residual heat from the reactor core while also preserving the structural integrity of the reactor during normal operation [2]. Multi-dimensional heat flow analysis is required to verify whether the RVCS has the intended capacity for heat removal, as it was constructed using a one-dimensional code [2].

The RVCS's flow path configuration and structure are depicted in Fig. 7. Introduced by the two intake ducts, the outside air travels down the gap between the concrete and the separator, where it is heated by radiation and convection in the annular space between the separator and the containment vessel. It then rises and is released through the two outlet ducts.

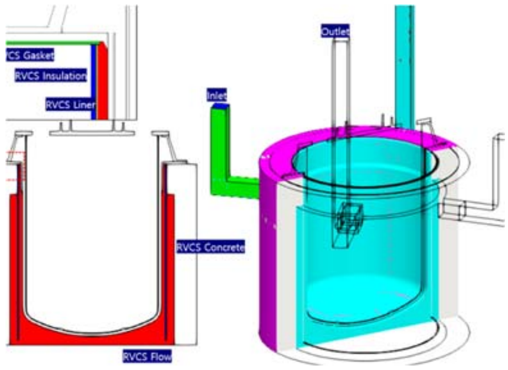

Fig. 7. Configuration of the SALUS RVCS

For natural convection, boundary conditions are crucial. The pressure, temperature, and velocity boundary conditions at the intake and outflow are displayed in Table I below.

Table I. Boundary conditions for the RVCS

	inlet	outlet
p	type calculated; value uniform 1e5;	type calculated; value uniform 1e5;
p_rgh	type fixedFluxPressure; gradient uniform 0; value uniform 1e5;	type uniformFixedValue; uniformValue constant 1e5; value uniform 1e5;
T	type inletOutlet; inletValue uniform 313.15; value uniform 313.15;	type zeroGradient;
U	type pressureInletOutletVelocity; value uniform (0 0 0);	type inletOutlet; inletValue uniform (0 0 0); value uniform (0 0 0);

Fig. 8 shows the analytical results of the RVCS, which removes heat using convective air from the outer wall of the containment vessel. The secondary flow happens after just passing the separator bottom, and the velocity rises along the upward flow route. The temperature of the outside air flowing along the downward flow path is rising by the containment vessel along the upward flow path. The naturally developed flow rate was calculated as 4.4 kg/s and the heat removal amount was approximately 0.48 MW.

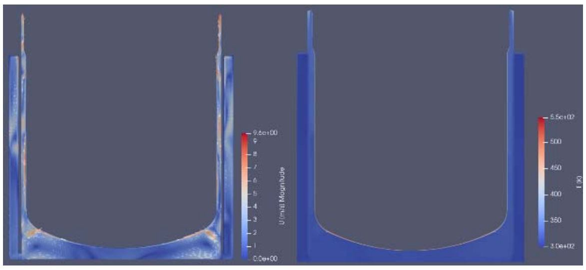

Fig. 8. Velocity (left) and temperature (right) distributions of the RVCS

A comparison of the 1D code and the 3D CFD result is shown in Table II. The air flow rate is lower than that of the one-dimensional code due to the different heat transfer mechanisms, but the amount of heat removal appears to be at a similar level.

Table II. Comparison of the 1D design code and the 3D CFD code for the RVCS simulation

	1D design code	CFD
Mass flowrate	4.96 kg	4.4 kg/s
Heat removal	0.49 MW	0.48 MW

3. Conclusion

Solids4Foam was utilized as a structural analysis solver to implement contact boundary constraints between structures. The solver was modified to include boundary conditions in order to apply hydrostatic pressure. Using the developed analysis system, the transient conditions of the SALUS were analyzed under arbitrary accident conditions and structural analysis was performed under transient conditions. The coupled analysis system's efficacy was validated.

Moreover, the multidimensional heat flow analysis was used to determine the quantity of heat removal for the SALUS RVCS design.

ACKNOWLEDGEMENT

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