Development of an OpenFOAM preCICE Adapter and a Preliminary Coupled Analysis of OpenFOAM and GAMMA+ Codes

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1. Introduction

A multidimensional thermo-fluid-structure integrated analysis environment is being constructed for SALUS, a long-life SFR, for design evaluation and structural integrity assessment of the reactor [1].

The integrated analysis consists of two main parts: linking the 3D thermal flow of the primary heat transfer system with the structural analysis, and linking the 3D thermal flow of the primary heat transfer system with the one-dimensional system analysis of the decay heat removal system / intermediate heat transfer system. The three-dimensional heat flow analysis covers the heat flow in the reactor sodium pool, argon gas, nitrogen gas, and air flow, and the structural analysis covers the reactor vessel, containment vessel, and reactor head.

Through our previous research [1], we have generated efficient grid systems for multiple regions of the SALUS reactor primary heat transfer system, reactor vault cooling system, and head access area and developed a fluid-structure integrated analysis system using OpenFOAM's thermo-fluid analysis solver chtMulti RegionSimpleFoam [2], structural analysis solver solid DisplacementFoam [2], and coupling library preCICE [3].

In this study, a preCICE adapter was developed for linking a three-dimensional thermal fluid analysis code with a one-dimensional system analysis code, and an fvOptions model was developed to apply the information transferred through the adapter to OpenFOAM's fvOptions. To validate the developed adapter, a simplified model of the reactor was applied and then preliminary calculation was performed by linking the chtMulti RegionFoam and GAMMA+ [4] codes for a transient condition of the SALUS reactor.

2. Developing a preCICE adapter and fvOptions model for OpenFOAM

2.1 An preCICE adapter and fvOptions model

The three-dimensional code and the one-dimensional system code are connected at the heat exchangers DHXs and IHXs as shown in Fig. 1. Currently, an adapter is provided to use the preCICE library for OpenFOAM solvers. However, this adapter can only convey temperature, energy, and shape changes at the boundary, not temperature, pressure, and energy information in the volume. In order to transfer information between codes in this area, an adapter for OpenFOAM was developed as shown in Fig. 2. The heat exchanger's heat transfer tube area is distinguished as a porous area, 'cellZone.' The adapter for GAMMA+, a system analysis code, was developed by modifying the code directly. This will be discussed in another paper.

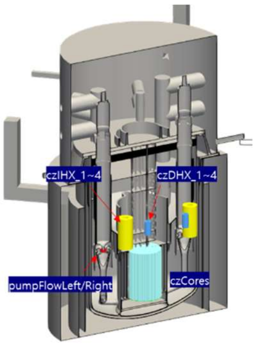

Fig. 1. HX porous regions for coupling with GAMMA+ code

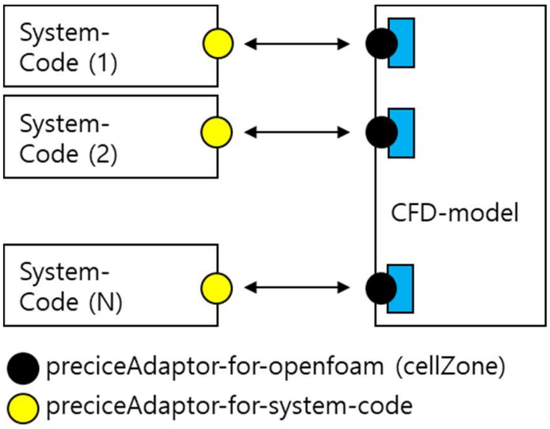

Fig. 2. Schematic of data-transfer at interfaces

The information that the OpenFOAM code should provide to the GAMMA+ code is stored in the preCICE variable 'cfd-variable' and vice versa in 'gamma-variable.'

The 'cfd-variable' is the extracted inlet temperature, inlet pressure, and outlet pressure for the 'cellZone' of the heat exchanger, and the 'gamma-variable' is the mass flow rate and heat removal rate of the heat exchanger shell side.

The OpenFOAM side adapter developed for this data exchange is 'libpreciceAdapterToCellZones.' The mass flow and heat transferred from GAMMA+ are processed as source terms in the momentum and energy equations through OpenFOAM's 'fvOptions,' and the OpenFOAM fvOptions model developed for this purpose is 'libprecicefvOptionToCellZones.'

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 outer cells adjacent to the upper and lower internal boundaries for the heat exchanger 'cellZone' were extracted and their values were averaged.

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.

To handle mass flow and energy with fvOptions, a new fvOptions model was developed based on the 'meanVelocityForce' fvOptions model.

2.2 Validation of adapter and fvOptions model

To validate the developed adapter and fvOptions model, the SALUS reactor was simplified into a two-dimensional model as shown in Fig. 3. The heat flow conditions are different from those of SALUS and this valiation's purpose is only to ensure that the developed adapter and fvOptions model work correctly. As initial conditions, the heat source in the core is set to 0.1 MW and the sodium flow rate in the pump is set to 0.1 m/s.

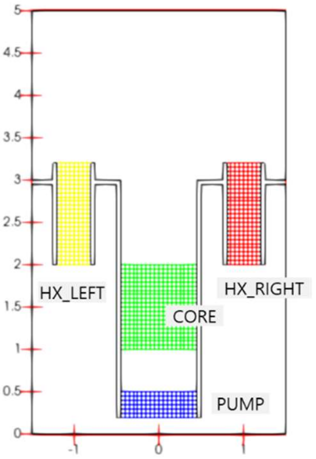

Fig. 3. A simplified 2D model for validation

Table I. Transient behavior of a simplified 2D model

Time [s]	dummySolver-1 (HX_LEFT)	dummySolver-2 (HX_RIGHT)
0 → 1800	mDot=0.5x6.7375kg/s Qloss=0MW	mDot=0.5x6.7375 kg/s Qloss=0MW
1800 → 2500	mDot=0.5x6.7375kg/s Qloss=0.5*0.1MW	mDot=0.5x6.7375 kg/s Qloss=0.5*0.1MW
2500 → 3000	mDot=0.6x6.7375kg/s Qloss=0.75*0.1MW	mDot=0.4x6.7375 kg/s Qloss=0.25*0.1MW

A dummy solver was written simply to serve as a sample code for the system analysis code that is linked to the OpenFOAM code. The dummy solver is passed a 'cfd-variable,' but does not utilize this information; instead, it varies the flow rate and heat input according to the scenario and passes it to the OpenFOAM code as a 'gamma-variable.' For comparison, the results are compared to an independent OpenFOAM analysis without using the preCICE library.

The transient scenarios are shown in Table I, with the flow rate and heat transfer varied over time for the heat exchanger.

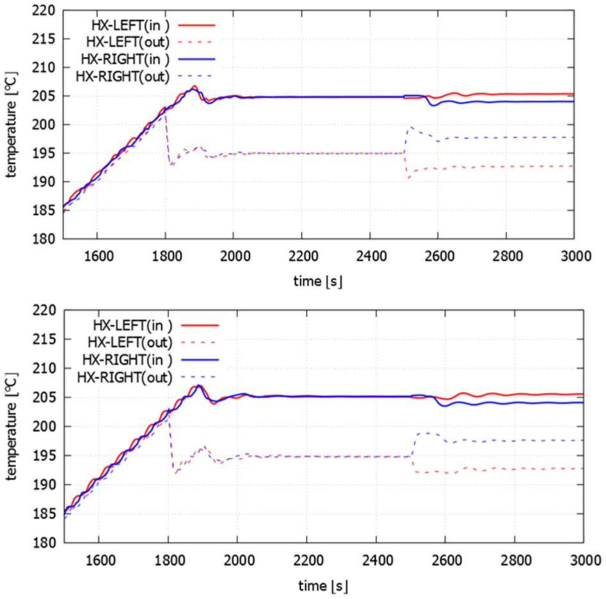

Fig. 4. Temperature variations via coupled analysis (top) and OpenFOAM independent analysis (bottom)

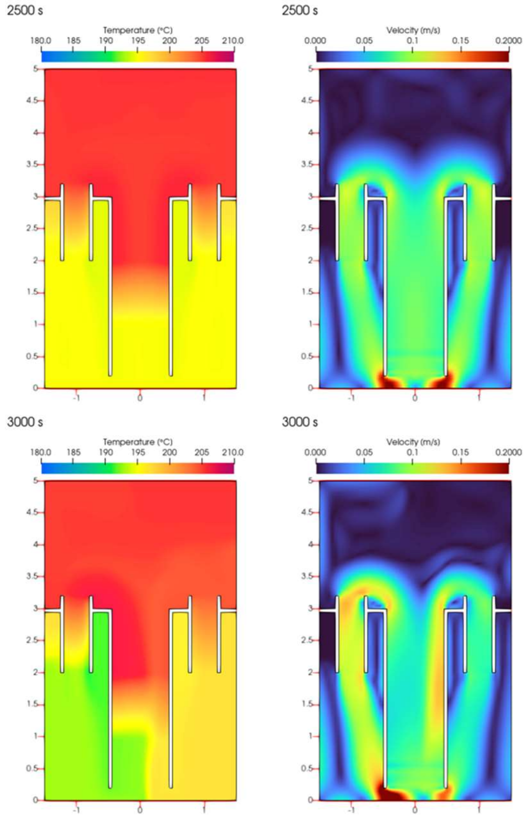

Fig. 5. Temperature and velocity fields of a coupled analysis

Fig. 4 shows the temperature evolution for the coupled analysis of the OpenFOAM solver with two dummy solvers and the analysis using only the OpenFOAM solver. The comparison of the two simulations shows that the developed adapter and fvOptions models are working properly.

Fig. 5 is the result of the coupled analysis and shows the temperature and velocity fields of the heat flow. From the stabilized heat flow field, it can be seen that the inhomogeneity of the heat flow field increases with the difference in heat transfer and flow rate between the heat exchangers.

2.3 Preliminary calculation of SALUS using the coupled analysis tool

For the chtMultiRegionFoam side, the developed adapter and fvOptions model were used, and the GAMMA+ code was modified to use preCICE to perform preliminary calculations using multidimensional integrated analysis by linking the SALUS three-dimensional heat flow field and one-dimensional decay heat removal system.

From the steady state, the heat in the core decreases according to the decay heat curve [5], the primary heat transfer system pump stops, and no heat is transferred to the IHX, and the heat is removed by the DHRS 4 trains. Strict neutron physics and analysis conditions for safety analysis were not applied, but the intention is to check the proper operation of this integrated analysis tool in the transient situation, and appropriate analysis conditions will be applied according to future accident scenarios.

Calculations were performed from the steady state of the nominal operation to 300 s after the shutdown of the reactor. In this case, heat from the core was also removed via the reactor vault cooling system and the head access area by forced convections. The temperature of the sodium pool dropped rapidly because all available means of cooling were taken into account.

Fig. 6 shows temporal variation of averaged temperatures of the hot and cold pools. Fig. 7 shows the temperature distribution in the reactor. Through the integrated analysis, it can be seen that the sodium pool is being cooled normally as the shell side flow rate and heat removal amount calculated in GAMMA+ are reflected based on the temperature and pressure information of the residual heat exchanger shell side.

4. Conclusion

A preCICE adapter and a fvOptions model were developed for the coupling of the three-dimensional thermos-fluid analysis code with the one-dimensional system analysis code, and their adequacy was verified for simplified 2D geometries. Preliminary calculations were also performed for the SALUS reactor using the developed preCICE adapter and fvOptions model and the GAMMA+ code modified to utilize preCICE. The preliminary multidimensional integrated analysis of SALUS confirms the adequacy of the tools developed in this work, and it is planned to perform the design and structural soundness assessment of SALUS by applying rigorous analysis conditions in the future.

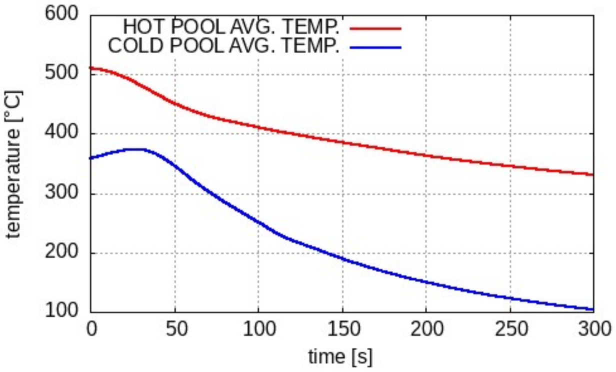

Fig. 6. Temperature variations from a coupled analysis of SALUS

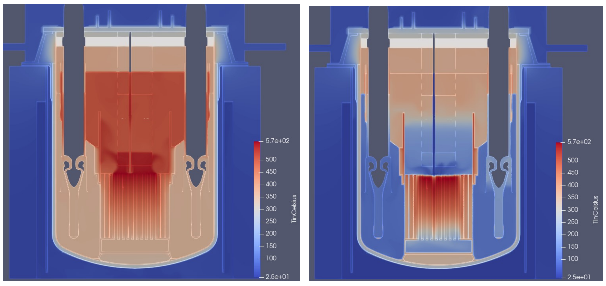

Fig. 7. Temperature fields from a coupled analysis of SALUS (left: 0 s, right: 300 s)

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