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Numerical modeling for Full-Core Thermal Hydraulic Analysis of SALUS Nuclear Reactor

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1. Introduction

From a geometry perspective, a nuclear reactor core can be defined, at its simplest, as a region of solids (duct walls, pins, etc.) and fluid (coolant) surrounded by a shroud. At a more precise level, the core is made up of hundreds of square or hexagonal ducts which contain a bundle of pins. Each assembly of pins is composed of a nuclear fuel assembly, a control rod assembly, and a reflector assembly according to its function, and each assembly is composed of a bundle of nuclear fuel pins, control rods, and reflector pins for each function.

Nuclear reactor core modeling can be done in various ways depending on the assumptions or purpose of reactor analysis. The simplest method is to analyze the reactor thermal hydraulics using a simple heat flux distribution model and flow resistance model in the core. Conversely, there is a high-precision analysis method that directly calculates the heat flux and flow resistance of the pins included in each assembly, but the amount of calculation is enormous, so it is very difficult to apply it in practice.

Meanwhile, to precisely analyze the flow and heat flux distributions at the core exit, it is necessary to vary the flow resistance model according to the geometry of the assembly (numbers and diameters of pins). And, when performing a transient analysis with high precision, it is necessary to couple the core kinetics and heat flow to consider reactivity feedback reflecting the arrangement of the assembly.

Therefore, a reactor core modeling technology suitable for the needs of various thermal-hydraulic analyses is required. In this study, we develop core modeling techniques and tools, especially geometry modeling and CFD mesh generation for a reactor core, required for coupled analysis of core kinetics and thermal hydraulics.

2. Methodology Development

2.1 SALUS core modeling

The SALUS core [1] consists of a total of 253 assemblies, including 112 nuclear fuel assemblies (inner 34 + outer 48 + outmost 30), 9 control rod assemblies, 78 reflector assemblies, and 54 shield assemblies. Fig. 1 shows the assembly arrangement in the SALUS reactor core.

Each pin bundle is contained in a hexagonal duct, a 3 mm thick duct with a gap of 4 mm between neighboring ducts. The total thickness of the duct wall and gap (10 mm) is approximately 5% compared to the width of the duct (169.05 mm) (d2dpitch in Fig. 2).

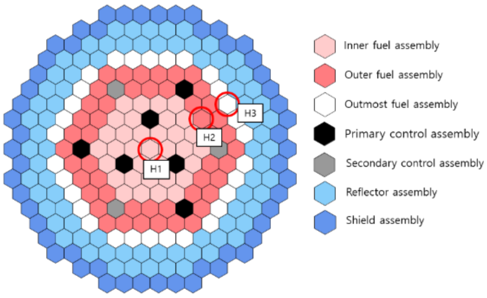

Fig. 1. Assembly arrangement in the SALUS reactor core.

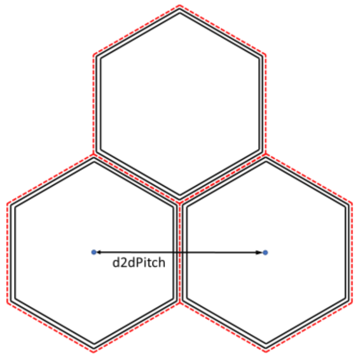

Fig. 2. Assembly duct configuration.

The most intuitive method is to simulate all duct inner walls, outer walls, and gaps and create a grid, but the amount of calculation is expected to increase. And because heat transfer through the duct wall is one-dimensional, using a three-dimensional grid is inefficient.

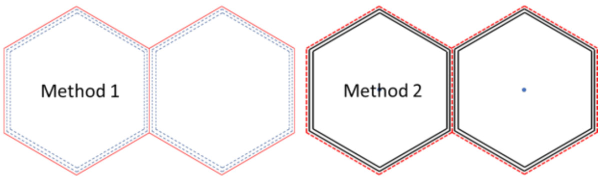

Fig. 3. Assembly duct and gap modeling.

Two models for heat transfer through the gap were considered as shown in Fig. 3. Method 1 in the figure is the use of the baffle model, which models the gap heat transfer by a 1-dimensional unsteady heat conduction normal to the duct wall with an augmented heat transfer by the gap flow. In Method 2, a 1-dimensional axial flow through the gap is considered for the convective heat transfer between the ducts.

To automate core geometry modeling, a Python program (coreModeller.py) running on the SALOME CAD [2] was developed. By entering the core design data of SALUS and loading coreModeller [3] in SALOME, core heat flow analysis modeling is automatically performed. Figs. 4 and 5 are plots to visualize the execution results of coreModeller for SALUS. Fig. 4 is the configuration of the pins installed in a duct, and Fig. 5 is the sub-channels of the assembly as the execution result of coreModeller.

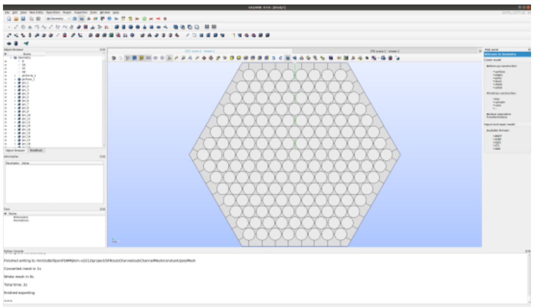

Fig. 4. Modeling of pin assembly by coreModeller.

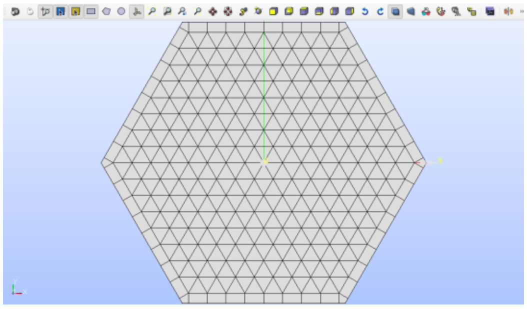

Fig. 5. Modeling of sub-channels in an assembly by coreModeller.

The coreModeller Python program can also conduct modeling of the assembly arrangement. The left side of Fig. 6 is the design of the reactor core, and the right side is the execution result of coreModeller, and it can be seen that the two arrangements of the core assemblies match.

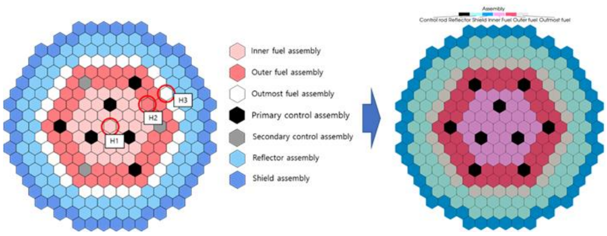

Fig. 6 SALUS core assembly modeling, left: design data, right: execution results of the geometry modeling tool.

The pin-shape-resolved modeling is limited to a single assembly thermal hydraulic analysis due to limitations in the CFD mesh size and the amount of calculation. The currently developed core shape modeling tool, coreModeller, can selectively use simple hexagonal sub-channel modeling and pin-to-pin sub-channel modeling (See Fig. 7). The mesh size of the pin-to-pin subchannel method for the fuel assembly is about 30 times larger than the hexagonal subchannel method as shown in Table 1. But it has the advantage of being able to apply well-developed models of friction on the pin surfaces.

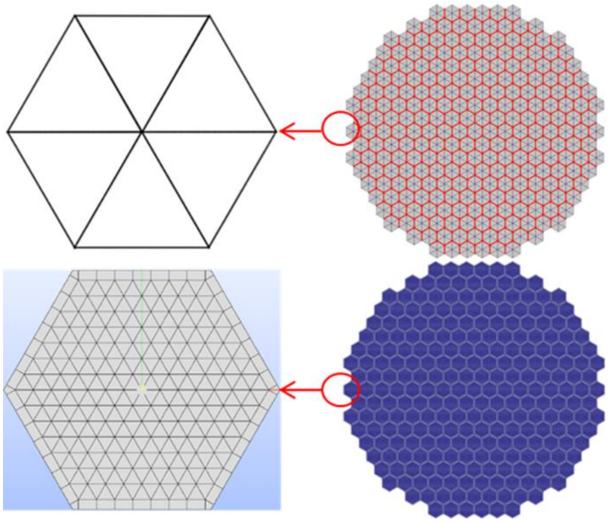

Fig. 7. Sub-channel modeling for the full core of SALUS.

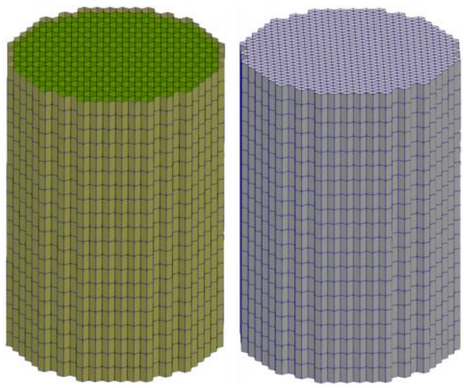

Fig. 8. SALUS core assembly modeling, left: duct wall grid, right: core flow field grid.

Fig. 8 of the modeled core shows the duct wall mesh and the internal core mesh.

Table. 1 Number of control volumes for the SALUS core assemblies.

Assembly	pin-to-pin subchannel	hexagonal subchannel
Fuel assembly CVs	341 X 112 X Nz	6 X 112 X Nz
CR assembly CVs	42 X 9 X Nz	6 X 9 X Nz
Reflector assembly CVs	78 X 78 X Nz	6 X 78 X Nz
Shield assembly CVs	18 X 54 X Nz	6 X 54 X Nz
Total CVs	45,626 X Nz	1,518 X Nz

2.2 Physical Model for Core Thermal Hydraulics

As described previously, the nuclear reactor core is composed of a large number of ducts and pins, and the amount of calculation is excessive to approach this using a turbulence-resolved method. Therefore, correlation equations developed through experiments and detailed analysis were combined. By doing so, the CFD approach can be effectively used to simulate the three-dimensional heat and fluid flow in a nuclear reactor core.

The ducts of the reactor core containing pin assembly are modeled as a porous medium. The governing equations for the turbulent coolant flow in a porous medium can be derived from Navier–Stokes equations via time and volume averaging. The Eqs. (1) – (3) are mass, momentum, and energy conservation equations [4], respectively, which are used for the full-core thermal hydraulic analysis.

$$\frac{\partial}{\partial t}(\gamma\rho) + \nabla\cdot(\rho\boldsymbol{U}_D) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho\boldsymbol{U}_D) + \frac{1}{\gamma}\nabla\cdot(\rho\boldsymbol{U}_D\otimes\boldsymbol{U}_D) = \nabla\cdot(\rho\nu_{eff}\nabla\boldsymbol{U}_D) - \gamma\nabla p + \gamma\boldsymbol{F}_g + \gamma\boldsymbol{F}_{ss} - (\rho\boldsymbol{U}_D\otimes\boldsymbol{U}_D)\nabla\frac{1}{\gamma} \quad (2)$$

$$\frac{\partial}{\partial t}(\gamma\rho e) + \nabla\cdot[(\rho e + p)\boldsymbol{U}_D] = \gamma\nabla\cdot(k_{eff}\nabla T) + +\boldsymbol{F}_{ss}\boldsymbol{U}_D + \gamma Q'''_{ss} + (k_{eff}\nabla T)\cdot\nabla\gamma \quad (3)$$

Currently, various pressure drop or flow resistance models are being developed. In this study, the Novendstern and Cheng-Todreas correlation models, which are representative flow resistance models for a wired-pin bundle, were added as core subchannel models.

- Novendstern drag model:
  $f_D = [A + B\cdot Re^{0.086}]^{0.885}$
- Cheng-Todreas drag model
  $f_D = (C_{fL}/Re)(1-\psi)^{1/3} + (C_{fL}/Re^{0.18})\psi^{1/3}$

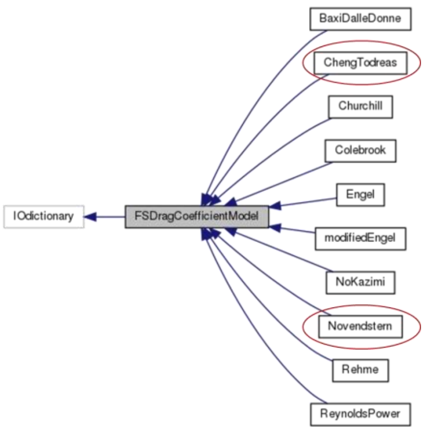

Fig. 9. Addition of Novendstern and Cheng-Todreas models for solid-fluid interfacial drag.

3. Test Run for Code Verification

To evaluate whether the core geometry modeling, core analysis grid generation, and core flow resistance model developed in this study work well overall, two verification test cases were made, which are flow in an assembly with the pin-to-pin subchannel method and flow in a full core of SALUS with the simple hexagonal subchannel modeling.

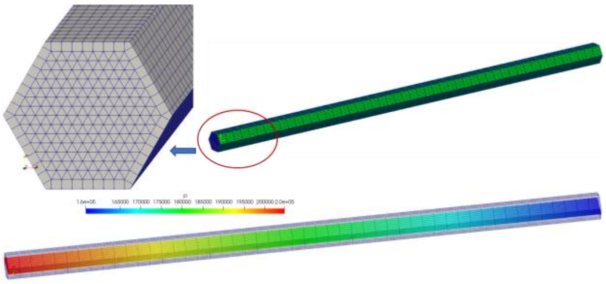

Fig.10. Modeling and simulation of a flow in an assembly.

Calculations were performed under uniform flow conditions at the inlet. Fig. 10 shows the pressure in the main flow direction. The flow field by the CFD simulation was well converged.

As shown in Fig. 11 calculations were performed for the full-core of SALUS under uniform flow conditions at the core inlet, and the pressure in the main flow direction was calculated. It was confirmed that all the three modeling works well.

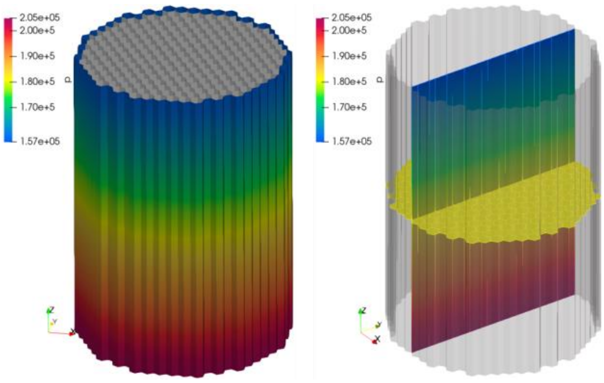

Fig.11. Cut-cell mesh around a sphere using a uniform background mesh

4. Summary and Future work

The goal of the current research is to develop a CFD methodology for full-core thermal hydraulics analysis coupled with neutronics, consisting of reactor core geometry modeling, full-core mesh generation, and solver development. Currently, verification of the models for thermal hydraulics is in progress.

As a future work, it is planned to couple the core kinetics and thermal hydraulics to consider reactivity feedback.

ACKNOWLEDGMENTS

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