Validation of RANS based CFD Methodology with STAR-CMM+ Code in a JNC Experiment of 169-pin Fuel Bundle

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1. Introduction

The Korea Atomic Energy Research Institute's Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) is a reactor that uses fast neutrons to generate fission reactions and transfers heat using sodium as a coolant. SFR (Sodium-cooled Fast Reactor) has attracted a lot of attention from several countries as a solution to the problem of sustainable energy supply, because it is compact and has high power density.

The high thermal energy generated in the fuel by nuclear fission could lead to material damage due to the thermal stresses created in the clad when significant temperature changes are subjected around its circumference. [1] Therefore, it is important to accurately predict the velocity and temperature profile of the coolant in the fuel assembly. In addition, determining the peak cladding temperature, hotspot location, and temperature gradient in hexagonal duct are important for design and safety analysis decisions. [2]

The temperature of the cladding and coolant of the nuclear fuel assembly in the core are investigated in order to meet the safety tolerance standards. Therefore, the core thermal design of the SFR must ensure adequate fuel thermodynamic performance. [3]

Many previous studies have been conducted in order to investigate the thermal-hydraulic behavior of nuclear fuel assemblies, using various turbulence models of computational fluid dynamic (CFD) [4-6]. However, very few studies investigate the thermal behavior of fuel assemblies at full scale using the SST turbulence model.

In this study, the results of the RANS steady analysis were comparison analyzed using the Japan Nuclear Cycle Development Institute (JNC) 169-pin fuel assembly heat transfer experiment data (MCH7-1789ABC) [7] to validate the RANS (Reynolds-Averaged Navier Stokes) based high-precision CFD analysis technique using STAR-CCM+ computational code.

2. JNC 169pin fuel assembly heat transfer Experiment

2.1 Experiment explanation

The JNC 169-pin experiment [7] was used as experiment data to validation the results of the experiment using multidimensional hydrothermal code AQUA [8], and is designed to validation the analysis method before application to large nuclear fuel assemblies such as 217-pin and 279-pin.

2.2 Experiment equipment

The experiment equipment is a simulated fuel assembly with an actual dimension heater pin. Table I. shows the shape data of the assembly. The assembly consists of 169 wire wound simulation fuel pins, and consists of 12 heated pins, 55 thermocouple mounting pins, and 102 unheated pins. The heating value per heated pin is 30 kW/pin, the axial calorific distribution is the same, and the heating length is 930 mm. 12 heated pins are installed, but the number of pins that can be heated at once is up to seven due to restrictions on power facilities.

2.3 Experiment condition

Experiment conditions are set in the range of $25 \sim 267\ W/cm$ line output, $50 \sim 1200\ L/min$ flow rate, and $200 \sim 500$℃ inlet temperature. A range of dimensionless numbers in the experiment conditions performed is Re = 2,500 ~ 55,000 and Pe = 13 ~ 230. In addition, the experiment cases and their conditions to be used in the validation of the analysis method are listed in Table I.

Table I. Experiment condition of 169-pin fuel assembly

case	**Heating value [kW]**	**Inlet volumetric flow rate [L/min]**	**Inlet velocity [m/s]**	**Inlet temperature [℃]**
MCH7-1789ABC-01A	13.51	98.85	0.451	393.78
MCH7-1789ABC-03A	27.45	198.64	0.905	392.28

3. Numerical Method

3.1 Computational grid system

Fig. 1 shows the computational grid configuration of the JNC 169PIN fuel assembly, it is composed of 55 million hexahedron elements. An innovative grid generation method using Fortran-based in-house code was applied [9]. Since heat transfer also occurs due to thermal conduction of the wire and the cladding, two interfaces were added by additionally creating a grid of rods and wires to simulate the same as in the experiment.

Because the actual wire shape is simulated without distortion of the shape, the prediction of the contact area between the wire and the rod can be made more accurately.

Simulation results using this methodology have been proven that it is possible to accurately predict the pressure drop and flow analysis of the fuel assembly [10].

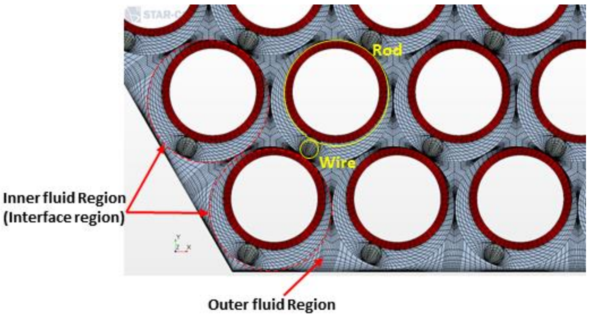


Fig. 1. Computational grid system of the JNC 169-pin fuel assembly

3.2 CFD Modeling

CFD analysis was performed using the MCH7-1789ABC [7] case to validation thermal data. The main design variables are shown in Table II.

Table II. Geometric of 169-pin fuel assembly

Geometry Parameters	Values
Number of pins	169
Pin diameter	6.5 mm
Wire diameter	1.26 mm
Wire lead pitch	238.9 mm
Pin pitch	9.12 mm
P/D	1.209
Heating length	930 mm
Total length	1500 mm

3.3 Boundary condition

Table III. describes the boundary conditions for CFD analysis. The mass flow rate is defined as JNP-169 pin (MCH7-1789ABC) experiment value, and the outlet is defined as a constant outlet input of 0 Pa.

Table III. Boundary condition of CFD analysis

Boundary domain	Condition	Value
Inlet	Mass flow rate	Variable [kg/s]
Outlet	Relative pressure	0 [Pa]
Rod wall	No slip	-
Wire wall	No slip	-
Duct wall	No slip Adiabatic	-

3.4 Turbulence model

Three major numerical analysis techniques can be used for turbulent flow fields: direct numerical simulation (DNS), large eddy simulation (LES), and Reynolds-averaged Navier-Stokes (RANS) simulation. RANS uses time-based, ensemble-averaged Navier-Stokes equations and models all of the effects from turbulence. Although RANS yields a lower resolution of analysis than DNS or LES, it is widely used in engineering applications due to the practical aspect of not requiring high-resolution calculation grids. The turbulence models for the RANS equations are for computing the Reynolds stresses tensor from the turbulent fluctuations in the fluid momentum. The turbulence models such as $k-\varepsilon$, $k-\omega$, and SST have become industry standard models and are commonly used for most types of engineering problems. The SST model solves the above problems for switching to the $k-\varepsilon$ model in the free-stream and the k-w model in the viscous sublayer [11]. Sensitivity studies of turbulence models such as Reynolds Stress Model (RSM), $k-\varepsilon$, $k-\omega$ and SST were performed on a 127-pin fuel assembly [12]. In that study, the friction factors with the SST model are 1.5–4.5% higher than that with the $k-\varepsilon$ model. The friction factor with the SST model is 1.4–1.5% smaller than that with the k-w model. Because the SST model switches to the $k-\varepsilon$ model and the $k-\omega$ model, the value of the friction factor with the SST model is between that with the $k-\varepsilon$ model and that with the $k-\omega$ model. The minimum grid scale on the fuel rod surface was $5.0\times 10E-7$ mm to capture the laminar to turbulent flow transition with the SST turbulence model the friction velocity $y+$ is approximately close to 2.5. In this study, the SST model of CFD was used for investigation.

4. result

For validation in the same manner as in the experiment, the temperature distribution near the upper end of the heated section (Z=1.28m) was examined, as shown in Fig. 2.

In addition, Fig. 3 shows the temperature measurement location of the Top of the Heated section in the experiment case MCH7-1789ABC. Fig. 4 shows the temperature measurement position according to the axial length of each mesh in the experiment case MCH7-1789ABC.

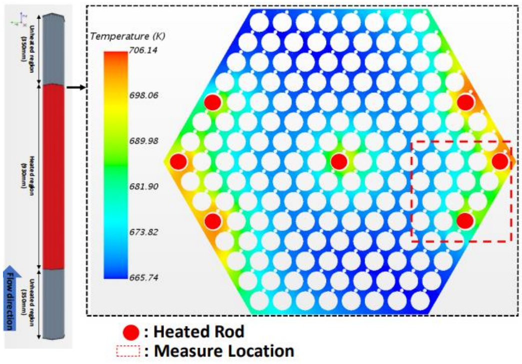


Fig. 2. Temperature distribution at the top of the JNC 169 PIN Heated section

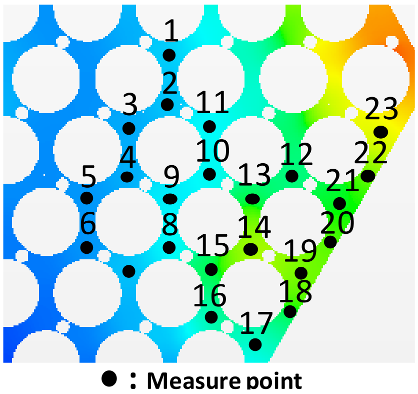


Fig. 3. Temperature measurement location of JNC 169 PIN

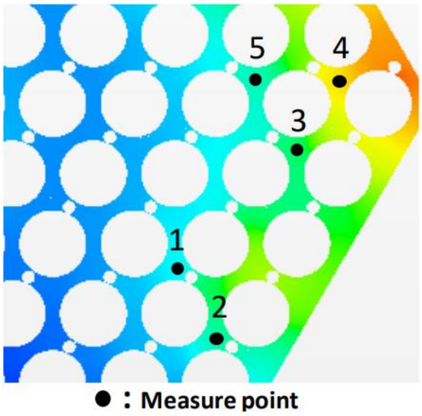
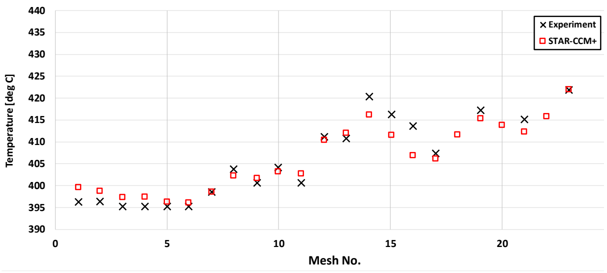


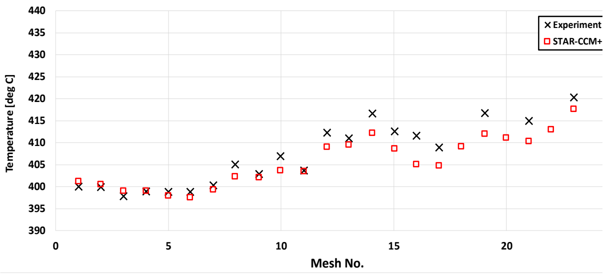
Fig. 4. Temperature measurement point of Axial Temperature

Mesh temperatures from No. 1 to 23 at the same location were measured even in STAR-CCM+ for analysis by comparing and analyzing the thermal data on the upper part of the heated section, and the results are shown in Fig. 7.

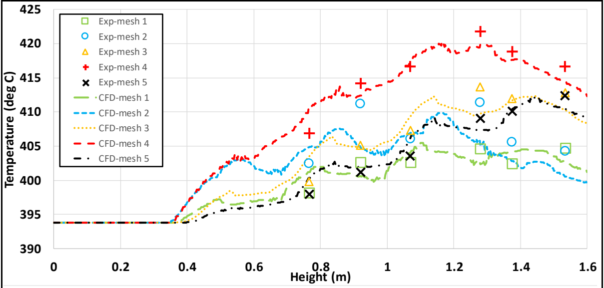
In addition, the temperature in No. 1 through No. 5 mesh was measured along the axial direction for analysis by comparing with temperature data according to the axial length of each mesh, and the results are shown in Fig. 8.



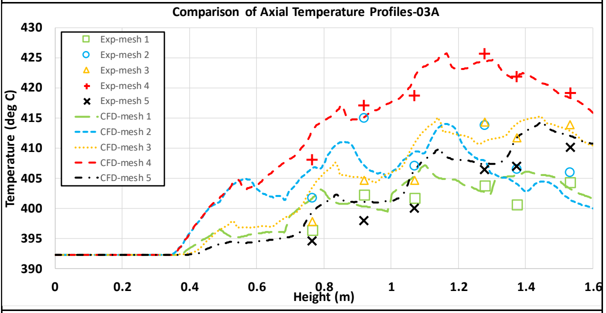
(a) Comparison of temperature distributions at The Top End of The Heated Section (MCH7-1789ABC-01A)



(b) Comparison of temperature distributions at The Top End of The Heated Section (MCH7-1789ABC-03A)



(a) Comparison of Axial Temperature Profiles (MCH7-1789ABC-01A)



(b) Comparison of Axial Temperature Profiles(MCH7-1789ABC-03A)

5. Conclusion

RANS based CFD Methodology validation was performed on JNC 169-pin fuel assembly experiment data (MCH7-1789ABC) for the high-precision CFD analysis technique using STAR-CCM+ code. CFD results are well matched with JNC 169 pin fuel assembly experiment data.

ACKNOWLEDGMENTS

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