Numerical Simulation Method of Thermal-hydraulics in Wire-wrapped Fuel Pin Bundle of Sodium-cooled Fast Reactor

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Abstract. A numerical simulation system, which consists of a deformation analysis program and three kinds of thermal-hydraulic analysis programs, is being developed by Japan Atomic Energy Agency in order to offer methodologies to clarify thermal-hydraulic phenomena in fuel subassemblies of sodium-cooled fast reactors under various operating conditions. In this paper, the authors focus on SPIRAL, which is one component code of the numerical simulation system and plays the role to simulate detailed local flow and temperature fields in a wire-wrapped fuel pin bundle, and give the outline of the code including a newly developed hybrid turbulence model and its applications to fuel subassembly thermal-hydraulic analyses as a validation study.

Key Words: Sodium-cooled fast reactor, Wire-wrapped fuel pin bundle, Thermal hydraulic numerical simulation, Validation

1. Introduction

Conceptual design studies of the Japanese Sodium-cooled Fast Reactor (JSFR) [1] are being performed towards the commercialization of next generation reactors by Japan Atomic Energy Agency (JAEA). In this design study, high performance core including high burnup and high power density is being pursued for obtaining economic competitiveness with future light water reactors along with assuring high levels of safety and reliability. For such pursuance, it is essential to clarify thermal-hydraulic phenomena in fuel subassemblies under various operating conditions such as normal operation, transient/accident conditions, or deformed pin-bundle geometry condition from the viewpoint of the assessment of fuel pin structural integrity.

The objective of this study is to offer methodologies for the clarification of thermal-hydraulic phenomena in a fuel subassembly. Experimental approach such as a mock-up test using liquid sodium generally requires both long term and high costs and often has difficulties in the measurement due to opaque liquid sodium, especially in complicated geometries like a wire-wrapped fuel pin bundle. Furthermore, there is not so much flexibility against the design change. Therefore, considering progress of computer systems and simulation technologies, JAEA has been developing a numerical simulation system that can substitute for the experiments as much as possible. In parallel, several water/sodium experiments have been carried out to create an experimental database for modeling and code validation.

Figure 1 shows the concept of the numerical simulation system developed by JAEA for thermal hydraulic analyses in a wire-wrapped fuel pin bundle including fuel deformation effect. This system consists of three kinds of thermal hydraulic analysis codes with a fuel deformation analysis code. Subchannel analysis code ASFRE [2] that uses more empirical

correlations in the physical modeling is applied to whole fuel subassembly simulations. ASFRE is manly used for design parameter analyses because of its high computation performance. SPIRAL [3] is a finite element method code and it contributes to local detailed simulations of flow and temperature fields in a fuel subassembly. This code also has a role to offer the thermal-hydraulic correlations to ASFRE. For instance, when ASFRE simulates temperature fields in a deformed fuel pin bundle with the help of the fuel deformation simulation code BAMBOO [4], SPIRAL can offer the data for improving the empirical correlations of ASFRE via detailed simulations using the deformed pin-bundle geometry. A body-fitted direct numerical simulation (DNS) code [5] offers fundamental data to improve turbulence models incorporated in SPIRAL. BAMBOO is a fuel deformation simulation code and it can calculate fuel pins and wrapper-tube deformation due to thermal expansion and irradiation effect (swelling). Combined use of ASFRE and BAMBOO enables us to calculate thermal hydraulic phenomena coupled with deformation. As one can easily imagine, the simulation cost extremely increases from subchannel analysis to the DNS and it is currently impossible to apply DNS to the whole subassembly simulation due to the limitation of current computer capabilities. Therefore, interactive use of these simulation codes that we propose is a practical way.

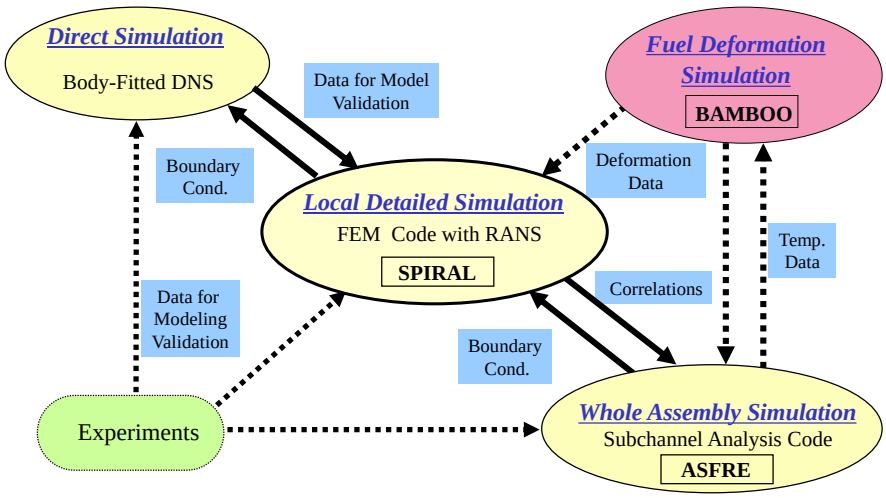


FIG. 1. Numerical simulation system for wire-wrapped fuel pin bundle

This paper focuses on SPIRAL and describes the outline of the numerical method of the code with a newly developed turbulence model. Then the applicability of this code to the prediction of pressure drop and temperature distribution in wire-wrapped fuel pin bundles are discussed through analyses of water/sodium experiments.

2. Outline of SPIRAL Code

SPIRAL is a finite element method code that can treat precisely curved boundary walls in a wire-wrapped fuel pin bundle. For numerical stabilization, one can choose the Streamline Upwind Petrov Galerkin (SUPG) method or the Balancing Tensor Diffusivity (BTD) method. Semi-implicit solution scheme (fractional step method) is used for time integration. As the pressure equation matrix solver, ICCG is applied. Energy conservation equations of coolant and structure are also solved and therefore temperature distributions of coolant and fuel pins can be calculated. The code is parallelized using MPI for enhancing simulation efficiency. Pre-processor is also available for the numerical grid generation using hexahedron and prism elements for a wire-wrapped fuel pin bundle by curvilinear coordinate system. This pre-processor can generate computational mesh arrangement completely fit to pin bundle

geometry, which is relatively coarse compared with the recent trend of very fine mesh arrangement from the viewpoint of saving the computation cost.

The turbulence models incorporated in SPIRAL are summarized in TABLE I. SPIRAL adopts several RANS models: High/low Reynolds (Re) number models and isotropic/anisotropic models can be selected for both flow field and temperature field simulations. In addition, a hybrid turbulence model is also available, which has newly been developed for accurate and efficient numerical simulations.

TABLE I: TURBULENCE MODELS INCORPORATED IN SPIRAL

	Flow Field	***Thermal Field***
High Re Number Model **Isotropic Model**	Modified k-ε Model (MMK) RNG k-ε Model	k_θ-ε_θ Model (Jones-Musonge Model)
Anisotropic Model	Algebraic Stress Model (ASM) (Rodi Model)	Algebraic Heat Flux Model (Rodi Model)
Low Re Number Model **Isotropic Model**	k-ε Model (Abe-Nagano-Kondoh Model)	k_θ-ε_θ Model (Abe-Nagano-Kondoh Model)
Anisotropic Model	Reynolds Stress Model (RSM) (Shima Model)	Turbulent Heat Flux Model (Launder Model)

3. Hybrid Two-Equation Turbulence Model

Considering the characteristics of coolant flow in fuel subassemblies, the flow changes widely from laminar to turbulence depending on the reactor operating conditions, and the local Re number also has a wide range due to the existence of wire-spacer and fuel pin deformation. On the other hand, existing two-equation turbulence models have the following characteristics: High Re number k-ε/k_θ-ε_θ model can calculate flow with relatively high efficiency but with less accuracy in low Re number regions. On the contrary, low Re number k-ε/k_θ-ε_θ model can simulate flow with high accuracy but with high computation cost due to the restriction of wall-adjoining element size (y^+ <1). By considering the combination of the advantages of each model, hybrid type k-ε/k_θ-ε_θ two-equation models have been developed. From approach of low Re number model, we picked up damping functions which are applied to outer layer elements to keep accuracy. From approach of high Re number model, we picked up wall functions which are applied to wall-adjoining elements (y^+ <200) to reduce the computation cost. Boundary conditions of k, ε, k_θ and ε_θ have been modified considering low Re/Pe number and Pr number effects. This hybrid turbulence model can decrease dependency of wall-adjoining element size on accuracy and can simulate flow and temperature fields with low cost and high accuracy in various Re number regions.

In the hybrid turbulence model for flow field, MMK model [6] from high Re number models and Abe-Nagano-Kondo (ANK) model [7] from low Re number models are selected and utilized as the base models. Reynolds stress and turbulent viscosity in the hybrid turbulence model are expressed by the following equations:

$$R_{ij} = \frac{2}{3} k \delta_{ij} - \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \tag{1}$$

$$\nu_t = C_\mu f_\mu f_{MMK} \frac{k^2}{\varepsilon} \tag{2}$$

Dumping function f_μ and correction function f_{MMK} are included in the turbulence viscosity. f_{MMK} is calculated by Eq. (3):

$$f_{MMK} = \begin{cases} \dfrac{\Omega}{S} & (\Omega \le S) \\ 1 & (\Omega \ge S) \end{cases} \tag{3}$$

where: $S = \sqrt{S_{ij}S_{ij}}$, $\Omega = \sqrt{\Omega_{ij}\Omega_{ij}}$, $S_{ij} = \frac{1}{2}(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})$, $\Omega_{ij} = \frac{1}{2}(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i})$.

This function has a role to suppress the overestimation of turbulent kinetic energy k when the flow impinges on the wall. k-ε transport equations are expressed as follows:

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\nu + \frac{\nu_t}{\sigma_k})\frac{\partial k}{\partial x_j}\right] + P_k + G_k - \varepsilon, \quad P_k = -R_{ij}\frac{\partial u_i}{\partial x_j}, \quad G_k = -g_j \beta R_{j\theta} \tag{4}$$

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\nu + \frac{\nu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}(C_{\varepsilon 1} f_{\varepsilon 1} P_k + C_{\varepsilon 3} f_{\varepsilon 3} G_k - C_{\varepsilon 2} f_{\varepsilon 2}\varepsilon) \tag{5}$$

where $R_{j\theta}$ is turbulent heat flux and calculated using k_θ and ε_θ. Damping functions are incorporated in the ε transport equation. These damping functions are adopted from AKN model. There are two kinds of advantages of ANK model adoption as a low Re number model. One is high accuracy especially for flow with separation and reattachment. This advantage is suitable for the flow in a wire-wrapped fuel pin bundle. Another is damping functions using y^*(= $u_\varepsilon y/\nu$) instead of y^+(= $u_\tau y/\nu$). Calculation of y^* does not require the distance from the wall and it enables simplified calculation process (programming) in the case of complicated geometries. The following damping functions and model constants are used in Eqs. (2), (4) and (5):

$$f_\mu = \left[1 + \frac{5}{R_t^{3/4}}\exp(-\frac{R_t^2}{200^2})\right]\left[1 - \exp(-\frac{y^*}{14})\right]^2, \quad R_t = k^2/\nu\varepsilon, \; y^* = u_\varepsilon y/\nu, \; u_\varepsilon = (\nu\varepsilon)^{1/4},$$

$$f_{\varepsilon 1} = f_{\varepsilon 3} = 1, \quad f_{\varepsilon 2} = \left[1 - 0.3\exp(-\frac{R_t^2}{6.5^2})\right]\left[1 - \exp(-\frac{y^*}{3.1})\right]^2, \tag{6}$$

$$C_\mu = 0.09, \quad \sigma_k = \sigma_\varepsilon = 1.4, \quad C_{\varepsilon 1} = C_{\varepsilon 3} = 1.5, \quad C_{\varepsilon 2} = 1.9$$

With respect to the near wall model for flow field simulations, a high precision wall function (Reichardt's law) is adopted instead of conventional log law functions:

$$u^+ = \frac{1}{\kappa}\ln(1 + \kappa y^+) + 7.8\left[1 - \exp(-\frac{y^+}{11}) - \frac{y^+}{11}\exp(-\frac{y^+}{3})\right] \tag{7}$$

Conventional wall boundary conditions for k and ε that are normally applied in high Re number models are also modified as follows:

$$k = \frac{u_\tau^2}{\sqrt{C_\mu f_\mu}} f(\nu_t), \qquad \varepsilon = \frac{u_\tau^4}{\nu_t}[f(\nu_t)]^2, \qquad f(\nu_t) = \frac{\nu_t}{\nu + \nu_t} \tag{8}$$

In the same way, a hybrid k_θ-ε_θ two-equation turbulence model for temperature fields has also been developed based on a low Re number model (ANK model) and a high precision

wall function for temperature fields (Kader equation) [8].

FIGURE 2 shows the comparison of k^+ $(=k/u_\tau^2)$ and k_θ^+ $(=k_\theta/\theta_\tau^2)$ in the near wall region calculated with the modified near wall model and with DNS [9,10]. Although discrepancy still remains, the modified near wall model can improve the reproducibility of the results with DNS.

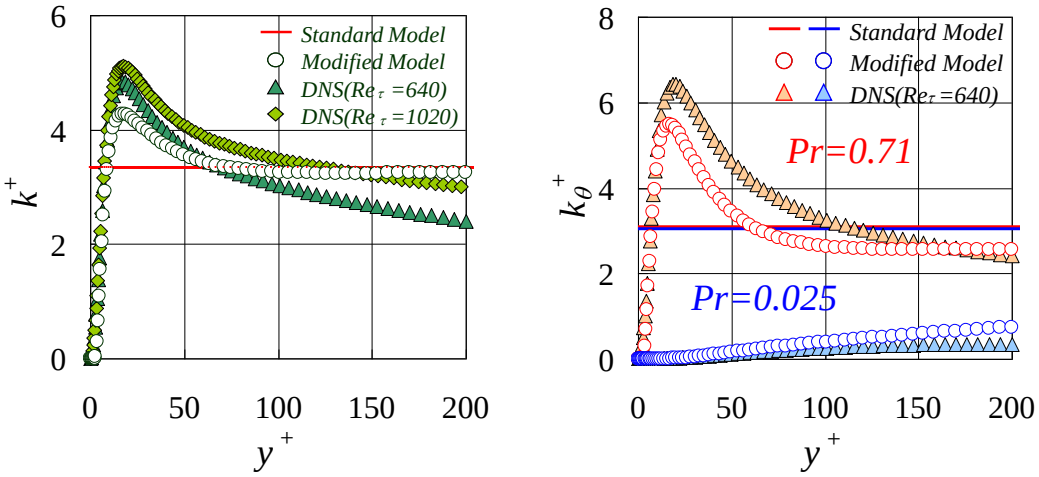


FIG. 2. Comparison of k^+ and k_θ^+ calculated by modified near wall model with DNS data

4. Application to Pressure Loss Prediction of Wire-wrapped Fuel Pin Bundle

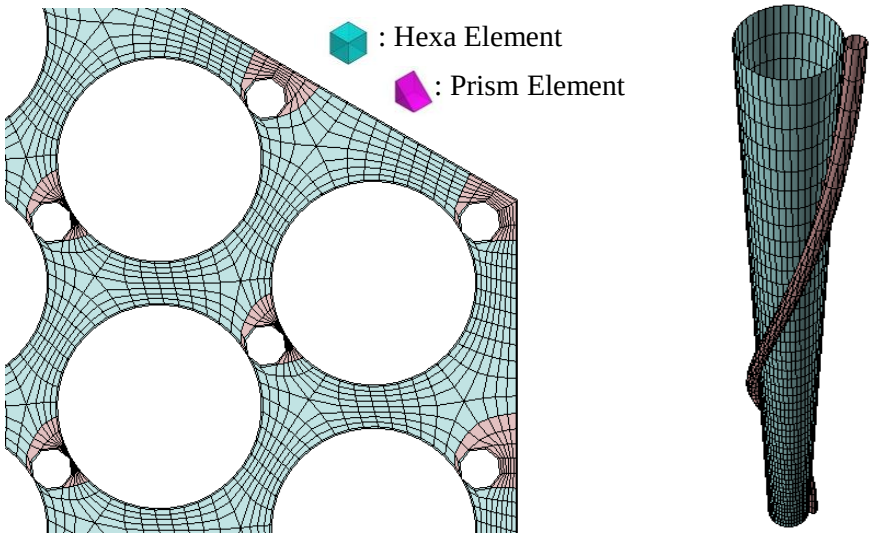
SPIRAL with the hybrid turbulence model was applied to analyses of three kinds of water mock-up experiments performed in JAEA using 127/169/271-pin bundles for confirming the applicability to pressure loss prediction. TABLE II summarizes the specifications of fuel subassemblies used in the experiments.

TABLE II: SPCIFICATIONS OF FUEL PIN BUNDLE MODELS

Number of Fuel Pins	127-Pin Bundle	169-Pin Bundle	271-Pin Bundle
Pin Array Pitch (P)	6.47mm	7.87mm	9.00mm
Pin Diameter (D)	5.50mm	6.50mm	7.50mm
Diameter of Spacer Wire	0.90mm	1.32mm	1.40mm
Wire-Wrapping Pitch (H)	209.0mm	307.0mm	165.0mm
Distance between Facing Wrapper Tube Walls	74.7mm	104.6mm	150.8mm
Hydraulic Equivalent Diameter	2.47mm	3.22mm	3.61mm
Bulk Mean Velocity	0.065~22.7m/s	0.057~9.7m/s	0.15~5.8m/s
Re Number	200~70,000	230~83,000	500~58,000
Number of Meshes	1.8 Million	2.4 Million	3.9 Million
Turbulence Model	Hybrid k-ε Model		
Wall Boundary Condition	Modified Near-Wall Model		
Inlet and Outlet	Periodic Boundary Condition		

These water experiments cover the wide range of Re number from laminar to turbulent flow. As an example of the computational mesh arrangement, a part of a horizontal cross section of

a pin bundle and a surface of one fuel pin with spacer-wire are shown in FIG. 3. This computational mesh arrangement is relatively coarse compared with the recent trend of such computations.



(a) Horizontal cross section (b) Fuel pin surface with wire-spacer

FIG.3. Example of computational mesh arrangement for wire-wrapped fuel pin bundle

FIGURE 4 shows the comparison of pressure loss coefficients between the prediction by SPIRAL and experimental data. Cheng-Todreas correlation [11], which is often used for subchannel analysis code, is also plotted in the graph as a reference. Although overestimation is still observed in low Re number (laminar flow) region, pressure loss coefficients in the three kinds of fuel pin bundles estimated from the results of the SPIRAL simulation are in good agreement with both the experimental data and the values estimated by Cheng-Todreas correlation in the wide range of Re number.

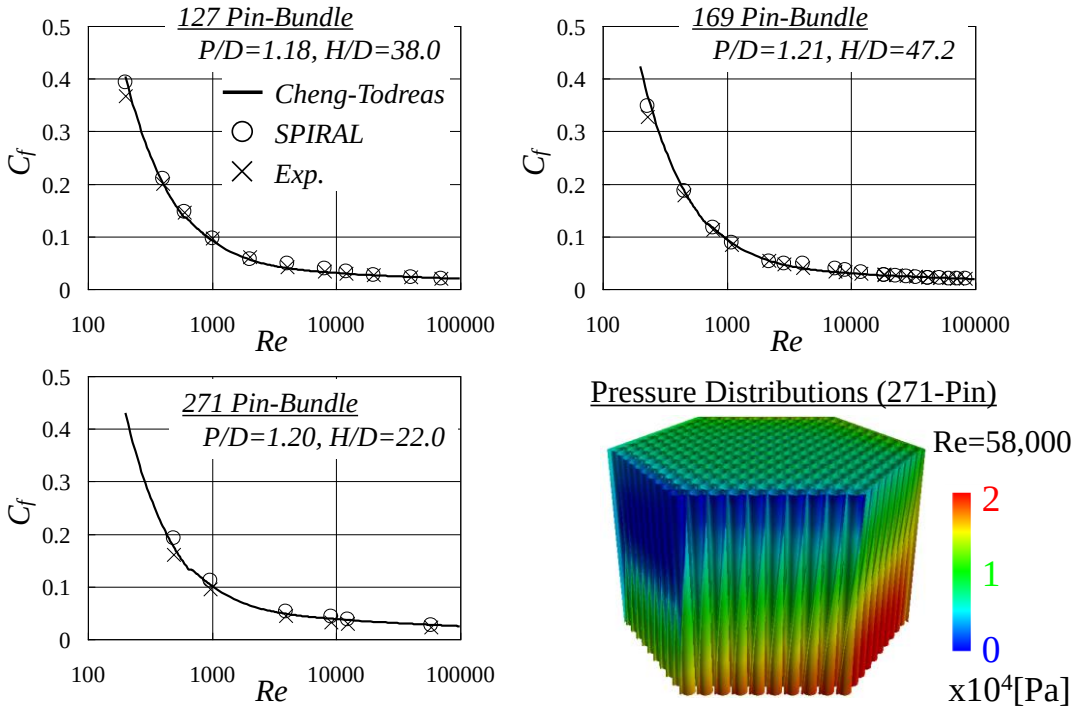


FIG.4. Comparison of predicted pressure loss coefficients in fuel pin bundles with measured data

5. Application to Sodium Temperature Field Prediction in 37-Pin Bundle

SPIRAL with hybrid turbulence model was also applied to an analysis of a sodium experiment performed in JAEA with a 37-pin bundle for confirming its applicability to the temperature field prediction. The specification of the pin bundle model and experimental conditions are summarized in TABLE III. In this numerical simulation, the mesh scheme topologically equivalent to those in Session 4 is used and the total number of meshes is approximately 2.8 million.

TABLE III: MODEL SPCIFICATION AND EXPERIMENTAL CONDITIONS

Specification of Fuel Pin Bundle Model	
Number of Pins:	37
Diameter of Pin:	6.50 [mm]
Pin Array Pitch:	7.87 [mm]
Diameter of Spacer Wire:	1.32 [mm]
Total Length of Pin:	2988 [mm]
Length of Heated Region:	930 [mm]
Wire-wrapping Pitch:	307 [mm]
Distance between Wrapper Tube Inner Surfaces:	50.4 [mm]
Experimental Conditions	
Flow Rate:	273 [l/min]
Total Power:	735 [kW]
Inlet Temperature:	397 [°C]
Average Velocity:	4.94 [m/s] (Re=51,000)

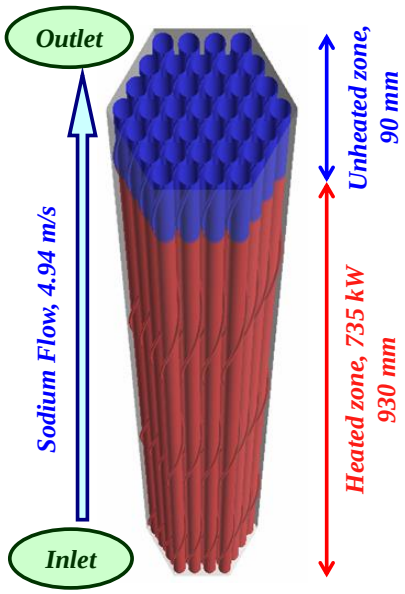
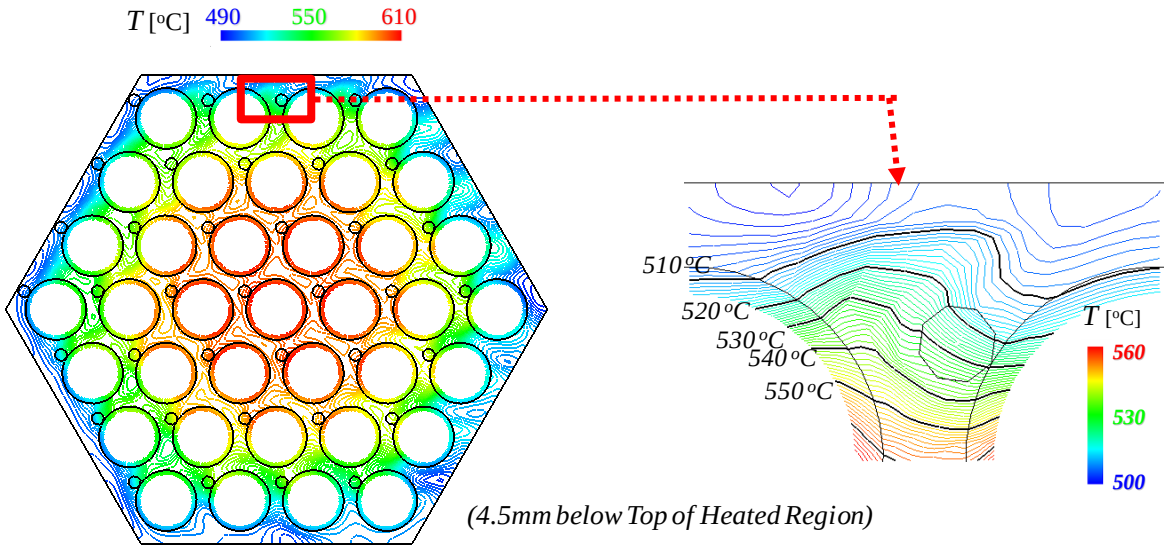


FIGURE 5 shows examples of the numerical simulation results. The left hand side indicates the predicted temperature field in the horizontal cross section of the pin bundle near the top of the heated region. Higher temperature appears in the central region because coolant flow rate in the central region is relatively low compared with that in the peripheral region. The temperature profile is axisymmetric due to the existence of the wire-spacer. The right hand



(a) Horizontal cross section (b) Local edge subchannel area

FIG.5. Predicted sodium temperature field near top of heated region

side indicates predicted local temperature field in an edge subchannel flow area. As shown in this figure, relatively large temperature difference is observed even in a local subchannel area. This means that the measured temperature may have a high sensitivity for the thermocouple position in a subchannel.

FIGURE 6 shows the predicted sodium temperature distribution with the measured data along the red line on the horizontal cross section at 4.5 mm below the top of the heated region. Temperatures averaged in each subchannel flow area are also plotted in the graph because non-negligible temperature difference appears even in a local subchannel area as shown in FIG. 5(b). Considering measurement error caused by thermocouple position shift, predicted temperature distribution is in good agreement with the experimental data.

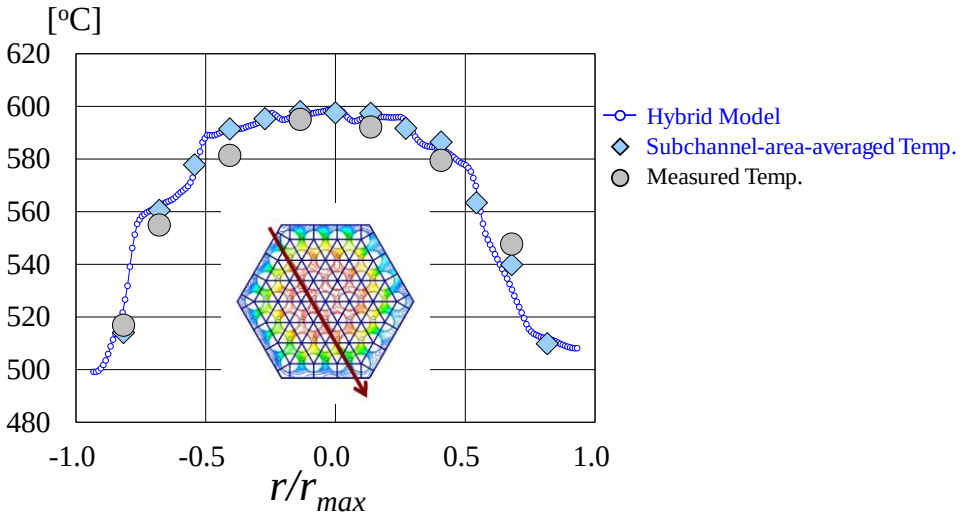


FIG.6. Comparison of temperature distribution between prediction and measured data

6. Summary and Concluding Remarks

In order to evaluate fuel pin structural integrity under various operating conditions including high burn-up one, a numerical simulation system for thermal hydraulics, deformation and their interaction in a wire-wrapped fuel pin bundle has been developed in JAEA. Detailed geometry of the wire-wrapped pin-bundle and turbulent flow passing over the wire are modeled by an FEM code named SPIRAL, that is one component code of this simulation system.

A hybrid turbulence model for both velocity and temperature field simulations has been developed based on a high Re number model (MMK k-ε model) and a low Re number model (ANK model) and has incorporated into SPIRAL. It enables efficient numerical simulations almost equivalent to high Re number models with high accuracy similar to low Re number models.

SPIRAL was applied to numerical simulations of flow and temperature fields in several types of wire-wrapped fuel pin bundles for the code validation. Pressure loss coefficients estimated by the simulations were in good agreement with measured data from laminar to turbulent regions. The simulated sodium temperature field in a wire-wrapped 37-pin bundle was also compared with the experimental data and showed good agreement. It was confirmed that SPIRAL can reproduce the flow and temperature fields in the elemental geometry of wire-wrapped pin-bundle.

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