Numerical Investigation of Heat Transfer Characteristics in Non-Uniform Power Distribution in Wire-Wrapped Pin Fuel Assembly

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1. Introduction

The fuel assembly of the SFR generally consists of several fuel pins, wires and a hexagonal duct. The fuel pins are arranged in a triangular pitch and wound with helical wire spacers. Because these wire spacers improve the mixing of the coolant, they have a great influence on the flow and heat transfer characteristics. It is important to predict and analyze the flow and temperature distributions for fuel safety.

Various fuel assembly analysis codes have been developed to predict the flow and temperature distribution in the subchannels [1-2] and many experimental studies on fuel assemblies have been conducted for the core thermal-hydraulic design of the SFR [3-4]. Recently, many CFD (Computational Fluid Dynamics) studies have been performed due to the development of computational resources [5-6]. Since detailed flow phenomena can be examined, numerical studies using CFD are being conducted more and more. In order to investigate heat transfer characteristics of fuel assemblies, it is important to analyze the temperature distribution not only in uniform power distribution but also in non-uniform power distribution. In this study, numerical investigations of heat transfer characteristics in non-uniform power distribution in SFR fuel assembly are presented. Numerical methods and validation results for wire-wrapped 37-pin fuel assembly are addressed.

2. Benchmark descriptions

The experimental benchmark is the Toshiba 37-pin SFR fuel assembly [7]. The objectives of the experiment are to measure the buoyancy effect on pin bundle heat transfer and to verify the validity of the analysis code (COBRA-IV-I) under low flow rates typical of natural circulation conditions. A series of experiments were conducted with the sodium heat transfer test loop at Toshiba Nuclear Engineering Laboratory. The loop simulates a heat transfer system for a typical LMFBR (Liquid Metal Fast Breeder Reactor) plant and a test assembly is installed in the primary loop. A layout view of the test assembly is shown in Fig. 1.

The test assembly contains 37 simulator pins within a hexagonal can, which has 50.4 mm flat to flat dimensions. The 6.5 mm diameter simulator pins are wound with wire-spacers 1.32 mm in diameter and the wire-wrap pitch is 307 mm. The triangular pitch between pins is 7.87 mm. Each simulator pin contains an electrical heated element to generate heat with a chopped cosine shape having a 1.21 maximum to average ratio. The rod bundle is grouped into three divided regions, which correspond to three power control units. The radial power skew within the rod bundle is produced by the three divided regions as shown in Fig. 2. Numerous thermocouples were embedded in the simulator rods to measure heat transfer characteristics with the pin bundle. The total length of the fuel assembly is 3043 mm, and the heated length is 930 mm. The detailed geometry parameters are listed in Table 1.

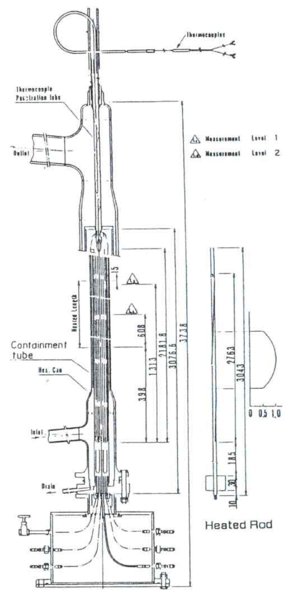

Fig. 1 Test section geometry for the Toshiba 37-pin bundle

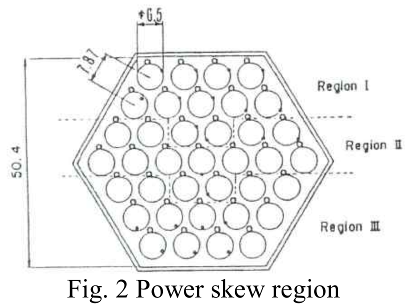

Fig. 2 Power skew region

Table 1. Design parameters of the Toshiba 37-pin fuel assembly

Parameters	Value (mm)
Pin number	37
Pin diameter	6.5
Pin pitch	7.87
Wire diameter	1.32
Wire lead length	307

Duct flat to flat distance	50.4
Total length	3043
Heated length	930

3. Numerical methods

A program that can automate the entire process of CFD for fuel assemblies was developed using open source software as shown in Fig. 3.

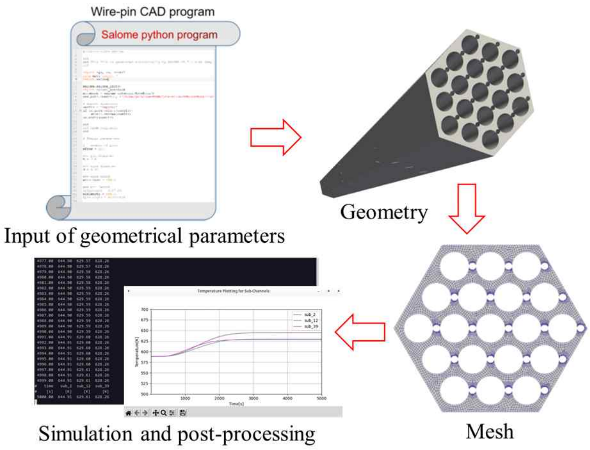

Fig. 3 Process of automated CFD system for fuel assemblies

The CFD simulations were performed using OpenFOAM code [8]. The geometry of the 37-pin fuel assembly for CFD simulations was modeled using SALOME [9]. The geometry can be generated automatically through input in python code. Meshes were generated according to the programmable mesh generation strategy for wire-pin bundles [10]. In the programmable mesh generation strategy, directional hybrid mesh is adopted. Unstructured mesh is used in spanwise or radial direction of the bundle, while structured mesh is used in axial or streamwise direction by extruding the spanwise mesh.

The computational meshes were created using OpenFOAM mesh generator snappyHexMesh. As shown in Fig. 4, meshes were densely created around wires that were relatively small in size compared to duct and pins, and the total number of computational mesh cells was determined to be about 11,000,000 considering computational resources and time. The three dimensional, steady state, compressible RANS (Reynolds Averaged Navier-Stokes) based simulations were performed. The mass flow rate was applied to the inlet and the pressure was given at the outlet, and no-slip condition was applied on the walls. The working fluid is sodium and the properties of sodium such as density, viscosity, specific heat, and conductivity according to temperature were applied. Heat transfer simulation was performed by giving heat flux to the walls of pins and the heat flux value was set the same as in the experiment. Numerical simulations were performed for three experimental cases, and the boundary conditions are shown in Table 2. The power peaking factor is the maximum to average power ratio in the radial direction. Based on previous numerical studies of SFR fuel assemblies, the SST (Shear Stress Transport) model was used as a turbulence model and y+ is about 10. Constant turbulent Prandtl number was used to predict the thermal eddy diffusivity and turbulent Prandtl number can be specified by the user.

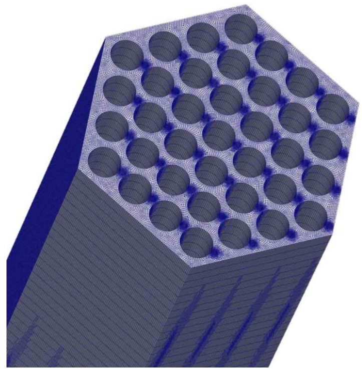

Fig. 4 Meshes for the Toshiba 37-pin bundle

Table 2. Boundary conditions of the Toshiba 37-pin fuel assembly

Run No.	Flow rate (l/m^3)	Inlet temperature (℃)	Power (W)	Power peaking factor
B37P02	89.2	211.3	53,580	1.0
E37P17	60.64	209.5	53,820	1.17
G37P22	59.48	205.8	54,570	1.34

4. Results

For the case with uniform power distribution (B37P02 case), the temperature distribution at the outlet of heated region is shown in Fig. 5. As shown in this figure, the temperature is high in the inner subchannels and low in the edge and corner subchannels. For comparison with the experiment, the subchannel temperatures were calculated and shown in Fig. 6. In the same way as the experimental results, the temperatures at the outlet of heated region were normalized by the temperature difference between the outlet and inlet. The CFD results qualitatively agree well with the experiment and slightly overpredict temperatures.

The normalized power distribution for the E37P17 case with a power peaking factor of 1.17 is shown in Fig. 7 and the temperature distribution at the outlet of heated region is shown in Fig. 8. Compared to the simulation for a uniform power distribution, the high temperature region is shifted upwards due to the power skew. The normalized power distribution for the G37P22 case with a power peaking factor of 1.34 is shown in Fig. 9 and the temperature distribution at the outlet of heated region is shown in Fig. 10. The largest power skew results in the largest temperature skew of all cases, with a large upward shift of the high temperature region.

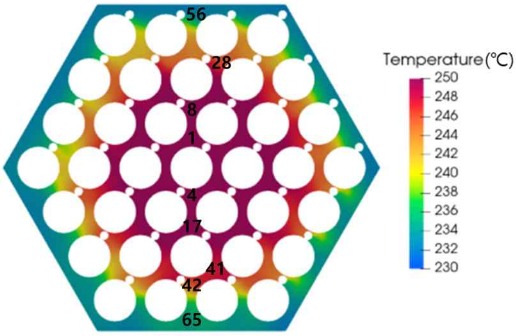

Fig. 5 Temperature distribution at the outlet (B37P02 case)

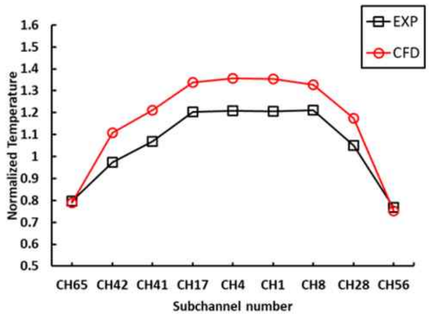

Fig. 6 Comparison of temperature distribution at the outlet (B37P02 case)

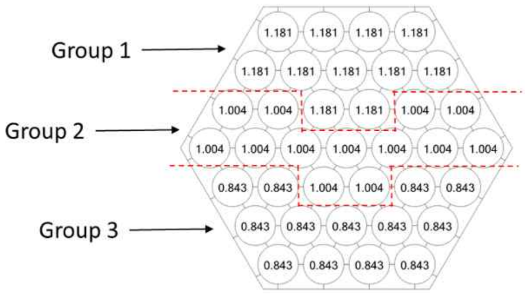

Fig. 7 Normalized power distribution (E37P17 case)

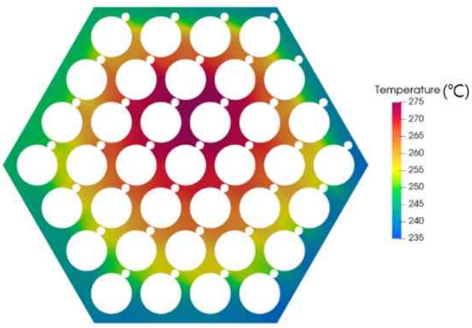

Fig. 8 Temperature distribution at the outlet (E37P17 case)

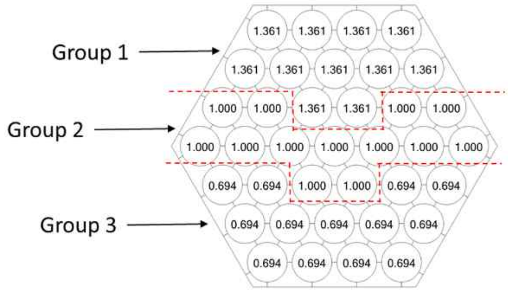

Fig. 9 Normalized power distribution (G37P22 case)

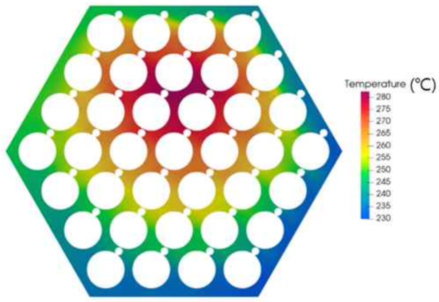

Fig. 10 Temperature distribution at the outlet (G37P22 case)

5. Conclusions

In this study, numerical investigations of heat transfer characteristics in non-uniform power distribution in wire-wrapped 37-pin fuel assembly are presented. A program that can automate pre-processing, simulation and post-processing of CFD was developed using open source software. The CFD simulations were performed using OpenFOAM code for the Toshiba 37-pin SFR fuel assembly. The temperature distribution at the heated outlet was investigated under uniform and non-uniform power distribution conditions to analyze heat transfer characteristics and to validate the numerical simulations.

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