Large-Scale Numerical Simulations of Multiphase Flow Behavior in an Advanced Light-Water Reactor Core

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Japan Atomic Energy Research Institute has been developing a reduced-moderation water reactor (RMWR) which is a candidate of advanced boiling-water reactors (BWRs) using a mixed-oxide fuel of uranium and plutonium. In the BWR core, water is boiled and becomes vapor. Hence, the flow configuration of water and vapor around each fuel rod surface is deeply related to the feasibility and safety of a reactor core. Since gap spacing between each fuel rod of the RMWR is very narrow in comparison with that of the current BWR, it is difficult to apply the two-phase flow characteristics obtained by the current BWR to the RMWR. Then, the large-scale simulations with the earth simulator were performed and the two-phase flow structure in the RMWR core was clarified quantitatively. On the other hand, although the coolant is 100% water at the core inlet, it almost becomes vapor at the core outlet. Moreover, the coolant is strongly influenced of flow disturbance due to the spacer installed in several axial positions. Then, direct numerical simulations were carried out to investigate turbulent structure around each fuel rod surface under the conditions of single-phase flow and Reynolds number of 78,000. The objective of the present numerical research is establishing the thermal design procedure of the RMWR core with a large-scale simulation, without performing real scale experiments.

Keywords: Advanced Light-Water Reactor, Two-Phase Flow, Water-Vapor Interface, Single-Phase Turbulent Flow, Direct Numerical Simulation

1. Introduction

Although subchannel codes [1–3] are used for the thermal-hydraulic analysis of fuel bundles in nuclear reactors from the former, lots of composition equations and empirical correlations based on experimental results are needed to predict the water-vapor two-phase flow behavior. When there are no experimental data such as the reduced-moderation light water reactor (RMWR) [4, 5] which is currently developed by the Japan Atomic Energy Research Institute, therefore, it is very difficult to obtain highly precise predictions.

The RMWR core has remarkably narrow gap spacing between fuel rods (i.e., around 1 mm) which are arranged at a triangular tight-lattice configuration in order to reduce the moderation of the neutron. In such a tight-lattice core, there is no sufficient information about the effects of the gap spacing and grid spacer configuration on the two-phase fluid flow characteristics. Then, the authors tried to analyze the water-vapor two-phase flow thermal-hydraulics in narrow parallel channels simulating a tight-lattice fuel bundle with spacers, using a large-scale direct simulation under the full bundle size condition. Although lots of calculation memory are required to attain the direct numerical simulation for the RMWR fuel bundle, the earth simulator in Japan enabled such a request.

The present large-scale simulations [6] were carried out using a newly developed two-phase flow analysis code which can predict the two-phase structure on the water-vapor interaction. Moreover, complicated turbulent structures [7] inside the fuel bundle were analyzed by a direct numerical simulation (DNS) under the single-phase flow condition.

2. Outline of RMWR core

The RMWR is an advanced type light-water reactor with a higher conversion ratio more than unity by controlling the water flow rates. In order to obtain a higher conversion ratio, it is expected from the results of the previous studies that a volume ratio of water and fuel must be decreased to about 0.25 or less. To satisfy this condition, the fuel bundle with a triangular tight-lattice arrangement is required: a fuel rod diameter is around 10 mm; and, the gap spacing between each rod is around 1 mm. Although the coolant is 100% water at the core inlet, it changes a mixture of water and vapor along the flow direction, and then, the vapor occupies 90% or more at the core outlet. Therefore, the RMWR has very severe cooling condition on the viewpoint of the thermal engineering. The RMWR consists of a core, control rod mechanism, separator, dryer and a pressure vessel. The RMWR core is mainly composed of fuel rods and spacers. The role of a spacer is as follows: to keep the gap spacing between fuel rods, and to restrict the motion of a fuel rod to the radial and circumferential directions.

3. Numerical Analysis

3.1. Two-Phase Flow Analysis

A new two-phase flow analysis code TPFIT was developed by Yoshida [8]. He made a new interface tracking method which can calculate precisely motion of the water-vapor interaction by improving a conventional method proposed by Youngs [9]. The surface tension is calculated using the continuum surface force model of Brackbill [10].

Figure 1 shows the analytical geometry of a simulated tight-lattice fuel bundle composing of 37 fuel rods. An axial length of the fuel bundle is 1260 mm. The water flows upward from the bottom. A flow area is a region in which deducted the cross-sectional area of all fuel rods from the hexagonal flow passage. The spacers are installed into the fuel bundle at the axial positions of 220, 540, 750 and 1030 mm from the bottom. The axial length of each spacer is 20 mm. The geometry and dimensions simulate the 37-rod bundle heat transfer test facility that was constructed to obtain the critical heat flux data on triangular tight-lattice coolant channels in the RMWR core. The fuel rod outer diameter is 13 mm and the gap spacing between each rod is 1.3 mm.

Inlet conditions of water are as follows: temperature 288˚C, pressure 7.2 MPa, flow rate 400 kg/m^{2}s, and the estimated Reynolds number is 40,000. On the other hand, boundary conditions are as follows: fluid velocities are zero on every wall (i.e., an inner surface of the hexagonal flow passage and outer surface of each fuel rod, and surface of each spacer); and, the velocity profile is uniform at the inlet of the fuel bundle. The void fractions of water and vapor were varied.

3.2. Single-Phase Flow Analysis

The computational conditions are as follows:

– Geometry is a circular duct, which simply simulates a complicated coolant channel of the RMWR core;
– Three-dimensional cylindrical coordinate is used;
– Reynolds number based on the wall shear velocity (Re_τ) is 2,000;
– Reynolds number based on the mean centerline velocity (Re_c) is 78,000;
– Analytical region is $5\pi R \times R \times 2\pi R$, where R is a radius;
– The number of computational grid is $4608 \times 1024 \times 1536$;
– Spatial descritization is the second-order finite difference method;
– Time descritization is the third-order Runge-Kutta and Crabk-Nicolson method;
– Periodic boundary conditions are applied to the axial and circumferential directions;
– Non-uniform mesh spacing is specified to the wall normal direction; and,
– No-slip condition is given to the wall surface.

4. Results and Discussion

4.1. Two-Phase Flow Analysis

Predicted axial velocity distributions in the horizontal direction are shown in Fig. 2. Here, Fig. 2 (a)–(c) are each result of different position: (a) is near the inlet section of A in Fig. 1; similarly, (b) is just the spacer position of B; and, (c) is just behind the spacer position of C. The velocity is indicated from blue to red using color gradation; blue and red mean 0 and 0.8 m/s, respectively. In Fig. 2 (a) the axial velocity distribution is almost uniform. It is accelerated by reduction of the channel cross-section due to existence of a spacer as can be seen in Fig. 2 (b). Behind a spacer, it is equalized as Fig. 2 (c) because the channel-cross section increases.

Figure 3 shows the predicted void fraction distribution around fuel rods in the horizontal direction. Here, blue and red show water and vapor. The void fractions of blue and red are larger and smaller than 0.5, respectively. Each fuel rod surface shown with a circle is enclosed with very thin water film, and vapor flows around the outside. In the region where the gap spacing between fuel rods is narrow, the bridge phenomenon in which adjacent fuel rods are connected by water film is confirmed. On the other hand, vapor flows through the central area of the fuel rods arranged in the shape of a triangular pitch. Because it is easier for vapor to flow this area, since the frictional resistance in this area is low compared with the narrow area. This result was in good agreement with the experimental result regarding to the following points:

1) The fuel rod surface is encircled with thin water film;
2) The bridge phenomenon by water film appears in the region where the spacing between fuel rods is narrow;
3) Vapor flows the triangular region where the spacing

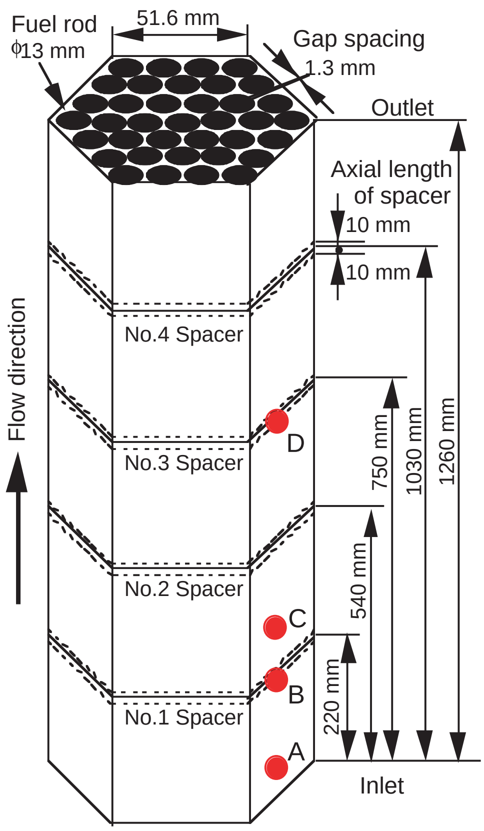


Fig. 1 Outline of three dimensional analytical geometry of a tight-lattice fuel bundle.

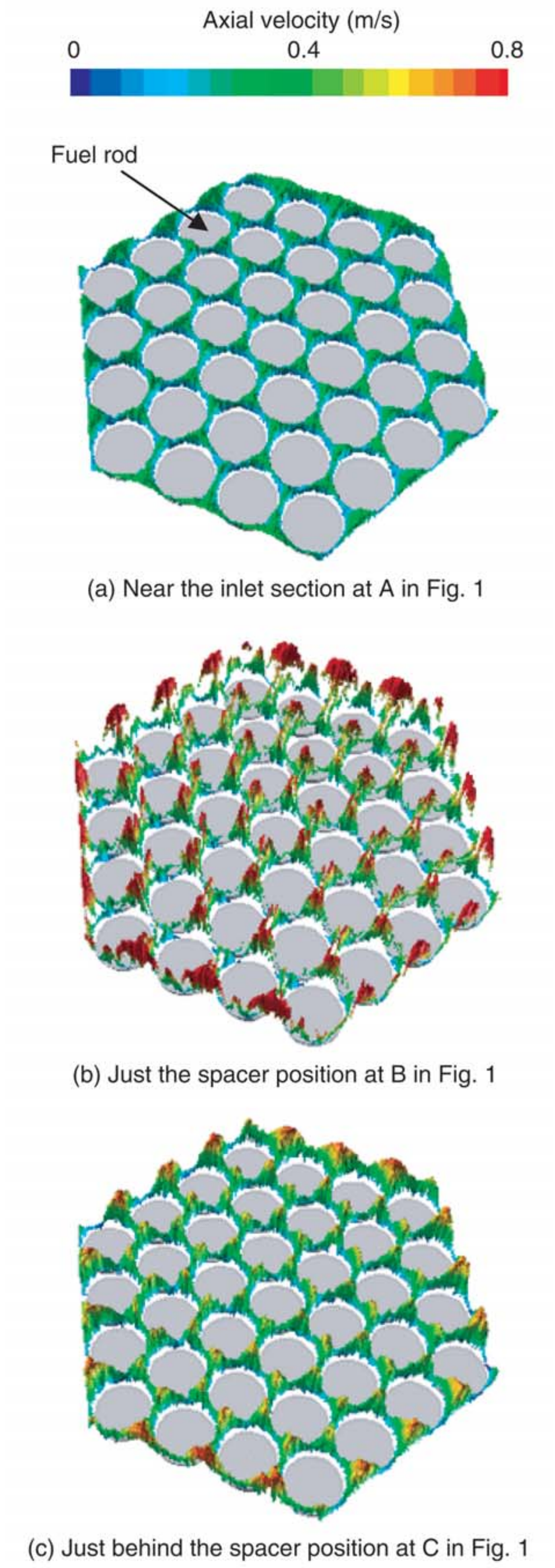


Fig. 2 Axial velocity distributions in the horizontal direction at three different axial positions.

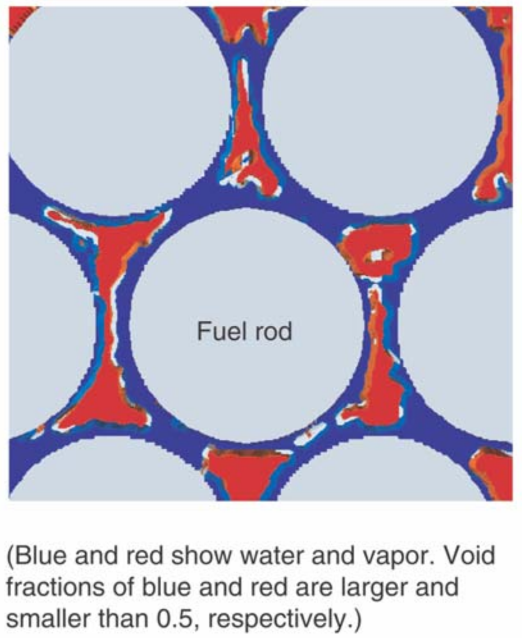


Fig. 3 Predicted void fraction distribution around fuel rods in the horizontal direction at the axial position D in Fig. 1.

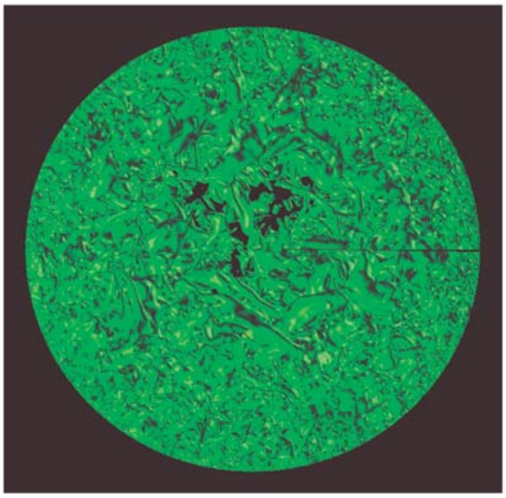
between adjacent fuel rods is large;

4) The triangular regions exist in the circumference of a fuel rod.

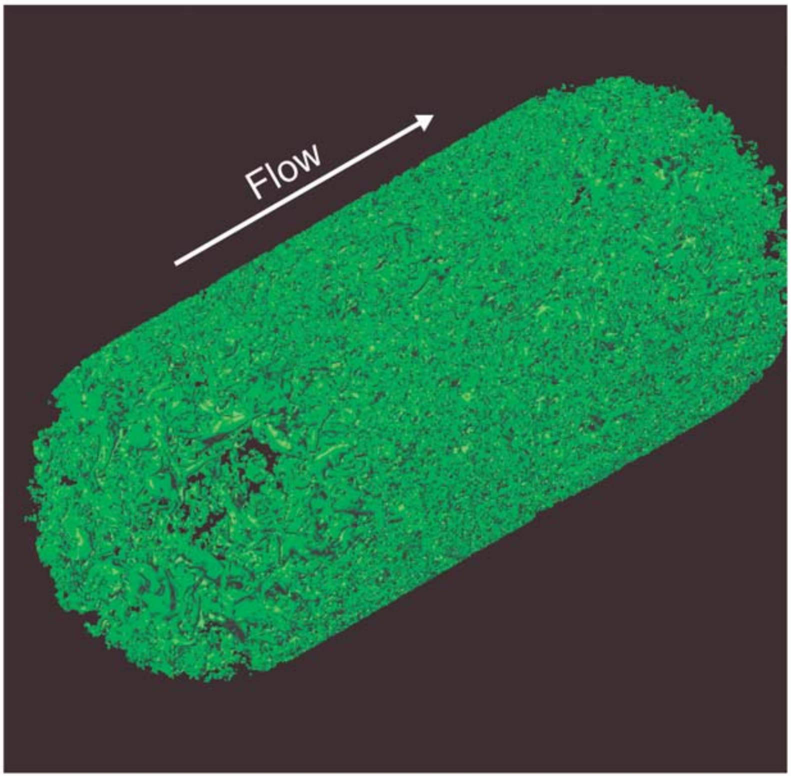
4.2. Single-Phase Flow Analysis

The turbulent flow analysis with DNS was performed under the simple circular duct geometry instead of the complicated coolant channels of the RMWR core. The conditions of Re_τ = 2,000 and Re_c = 78,000 satisfy the outlet condition of the RMWR core that is almost occupied with vapor. Specifications of the earth simulator for the present simulation are as follows: the number of used central processing unit is 1,152 and it corresponds to 144 nodes; the total memory is 2 terabytes; and, the total number of computational grid is 7,200 million points. The scale of the present DNS attained No.1 in the world to the field of a turbulent shear flow computation.

In general the turbulent flow consists of lots of vortexes. Figure 4 shows predicted the turbulent structures inside the



(a) Cross-sectional view



(b) Three-dimensional view

Fig. 4 Predicted turbulent structures inside a circular duct; Reynolds numbers based on the wall shear velocity and mean centerline velocity are 2,000 and 78,000, and the scale of this Reynolds number is the highest in the world to the field of a turbulent shear flow computation.

circular duct. The large and small streaky structures of turbulence can be observed. By the present large-scale DNS, the correlation of the micro-scale unisotropic turbulent structure near the inner wall of the circle duct and the large-scale turbulent structure inside a core region of that in a high Reynolds number region of 78,000 became clear quantitatively for the first time in the world.

5. Conclusions

The water-vapor two-phase flow characteristics in the RMWR fuel bundle were analyzed numerically using a newly developed two-phase flow analysis method and the earth simulator. The high prospect was acquired on the possibility of establishment of the thermal design procedure of the advanced type light-water nuclear reactor with large-scale simulations. Moreover, the results of DNS were useful to clarify the physical phenomena in nuclear fuel bundles under the conditions of a single-phase flow and high Reynolds number. Furthermore, if the results of DNS are systematized as a database, it will become greatly effective in construction of new turbulence models, or improvement in the prediction accuracy of engineering design of the nuclear reactors.

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