A Large-Scale Parallel Computing of Boiling Two-Phase Flow Behavior in Advanced Light Water Reactors

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Abstract. In order to predict the water-vapor two-phase flow dynamics in a fuel assembly of an advanced light-water reactor, a large-scale parallel computing of boiling two-phase flow was carried out. Conventional analysis methods such as subchannel codes and system analysis codes need composition equations based on the experimental data. In a case that there are no experimental data regarding the thermal-hydraulics in the tight-lattice core, therefore, it is difficult to obtain high prediction accuracy on the thermal design of the advanced light-water reactor core. Then, a mechanistic two-phase flow simulation method was proposed and also two simulation codes were developed. One is the TPFIT code based on the interface–tracking method and the other one is ACE-3D based on the two-fluid model. So both codes are fully parallelized, high performance computing is enable each other. This paper describes the boiling two-phase flow simulation results with TPFIT and ACE-3D. From the present results, the high prospect was acquired on the possibility of establishment of a new thermal design method for the advanced light-water reactor cores by the large-scale simulation only.

Keywords: fluid dynamics, large-scale simulation, parallel computing, boiling two-phase flow, fuel assembly, nuclear reactor.

1 Introduction

Subchannel codes [1]-[3] and system analysis codes [4],[5] are used for the thermal-hydraulic analysis of fuel assemblies in nuclear reactors from the former, however, many 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 an advanced light-water reactor [6]-[8] named as the reduced moderation water reactor (RMWR), therefore, it is very difficult to obtain highly precise predictions. Then, the authors proposed a new thermal design method for nuclear reactors by the large-scale simulation only [9]. Although this method needs a lot of calculation resources, the earth simulator [10] enabled such a request. This paper describes the predicted results of boiling two-phase flow behavior in a tight-lattice fuel assembly of the RMWR core.

2 Outline of RMWR

The RMWR can be expected to attain a higher conversion ratio of more than 1 by reducing the moderation of neutrons, i.e. reducing the core water volume. This characteristic is favorable for the long-term energy supply with uranium resources, the high burn-up and long operation cycle achievement, and the multiple recycling of Plutonium. In order to obtain the high 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 assembly 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% liquid water at the core inlet, it changes into 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.

Figure 1 shows a bird-eye view of the RMWR. It consists of a core, control rod, separator and dryer region, and a pressure vessel. The pressure vessel diameter and height are around 9 and 19 m. The core region is composed of 282 fuel bundles. Each fuel bundle has a hexagonal shape horizontally. A length of one side of a hexagonal shape is about 0.13 m and the axial length of a fuel bundle is about 2.9 m. A heating section in the core consists of two seed and three blanket regions and its length is about 1.3 m (i.e., around 0.2 m in each seed region and 0.3 m in each blanket region). In the core, MOX (mixed oxide) is used to the seed region and then the depleted UO_2 is used to the blanket region.

3 Numerical Analysis

3.1 Two-Phase Flow Analysis Codes

A two-phase flow analysis code based on the interface-tracking method [11] was developed and named TPFIT. It is discretized using the CIP method [12]. The surface tension is calculated using the continuum surface force model proposed by Brackbill [13]. The tracking of an interface between the liquid and gas phase is accomplished by the solution of a continuity equation for the volume fraction of a couple of the phases. It was completely parallelized using MPI. The parallelization performance of TPFIT is shown in Table 1.

On the other hand, a three-dimensional two-fluid model code ACE-3D [14] was developed for predicting the two-phase flow behavior in nuclear reactor cores. This has a boundary-fitted coordinate method to simulate complex geometries as fuel bundles and a fully-parallelized code with MPI. The parallelization performance of ACE-3D is shown in Table 2.

3.2 Analytical Model and Boundary Conditions

Figure 2 shows the analytical geometry consisting of 37 fuel rods and a hexagonal flow passage. The geometry and dimensions simulate the experimental conditions [15]. Here, the fuel rod outer diameter is 13 mm and the gap spacing between each rod is 1.3 mm. The length of one hexagonal side is 51.6 mm. An axial length of the fuel bundle is 1260 mm. The water flows upstream from the bottom of the fuel assembly.

Spacers are set to four axial positions in order to keep the gap spacing between fuel rods and also to restrict the movement of a fuel rod to the radial and circumferential directions. The outline of the shape of a currently designed spacer is shown in Fig.3. Its shape is like a honeycomb. The spacer is installed around each fuel rod with a triangular tight-lattice arrangement in the horizontal direction. The fuel rod is supported by three spacer ribs, which are set to the inside of the spacer. In Fig.3 the gap spacing is 1.3 mm and thickness of the spacer is 0.3 mm.

In case of the TPFIT code, the non-uniform mesh division was applied. The minimum and maximum mesh sizes were 0.01 and 0.3 mm. An example of the calculation mesh division in the horizontal cross-section is shown in Fig.4. In such a case the number of mesh division in the x and y directions are 632 and 555, and the number of mesh division in the z direction is varied from 150 to 600. The maximum number of mesh division in the x, y and z directions was around 210 million.

Figure 5 shows the computational grids for the ACE-3D code, which corresponds to one sixth of a horizontal plane. A non-uniform mesh division was applied. The total number of mesh division in the x, y and z directions are 120 million.

Inlet conditions of water are as follows: temperature 283°C, pressure 7.2 MPa, and flow rate 400 kg/m^2s. Moreover, boundary conditions are as follows: fluid velocities for x, y and z directions 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); velocity profile at the inlet of the fuel assembly is uniform; and, heat flux of each fuel rod was given to the heating section.

4 Results and Discussion

4.1 Predicted Results with TPFIT

Figure 6 shows the void fraction distributions around fuel rods in the horizontal direction. Here, the void fraction is defined as the ratio of the gas flow (i.e., vapor) cross sectional area to the total cross sectional area of the flow channel. In Fig.6 the void fraction is indicated using color gradation from blue to red: 100% liquid water at blue and 100% non-liquid vapor at red. Fig.6 (a) is the predicted result around the axial position A in Fig.2. Each fuel rod surface shown with a circle is enclosed by thin water film, and vapor flows the outside. In the region where the gap spacing between fuel rods is narrow, the bridge formation of water in which adjacent fuel rods are connected by the water film is confirmed. On the other hand, vapor flows through the center area of the fuel rods arranged in the shape of a triangular pitch. Because it is easier for vapor to flow, since the frictional resistance in this area is low compared with the narrow area.

Figure 6 (b) is an example of the experimental result of the void fraction distribution around the axial position A in Fig.2, which is obtained by an advanced neutron radiography technique which was developed by Kureta [16]. The general neutron radiography technique has been established based on the following features; neutron passes through materials but is blocked by water. It is possible to measure the void fraction inside a fuel bundle by non-contacting using this technology. The result was translated by the experimental result using a new image processing procedure. A tendency of the water and vapor distributions shown in Fig.6 (a) and (b) is in good agreement. Namely,

1) The fuel rod surface is encircled with thin water film;
2) The bridge formation by water film appears in the region where the gap spacing between fuel rods is narrow;
3) Vapor flows the triangular region where the gap spacing between adjacent fuel rods is large; and,
4) These triangular regions exist in the circumference of a fuel rod.

Figure 7 shows the two-phase flow configurations around a spacer of the axial position B in Fig.2. Fig.7 (a) shows the water distribution. Here, blue represents a region where the void fraction is 0.1 or less and it is occupied with water of about 100%. Moreover, Fig.7 (b) shows the vapor distribution. Here, red represents a region where the void fraction is 0.9 or more and it is occupied with vapor of about 100%. Much water can be seen at to the circumference of a fuel rod. Water exists as the liquid film. A bridge formation can be checked. In addition, much vapor exists along the spacer in the axial direction. Thus, a difference in the water and vapor distributions in the vicinity of the fuel rods and spacer is clear.

Figure 8 shows an example of the predicted vapor structure around the axial position B in Fig.2. Here, the distribution of void fraction within the region from 0.5 to 1 is shown: 0.5 indicates just an interface between the water and vapor and is shown by green; and 1 indicates the non-liquid vapor and is shown by red. Vapor flows from the upstream to downstream like a streak through the triangular region, and the interaction of the vapor stream to the circumferential direction is not seen. On the other hand, since the vapor is disturbed behind a spacer, the influence of turbulence by existence of the spacer can be predicted.

4.2 Predicted Results with ACE-3D

A three-dimensional predicted result of void fraction in a fuel bundle is shown in Fig.9. The color contour indicates the void fraction distribution; blue is the liquid water (i.e., void fraction is 0) and red is the mixture of water and vapor (void fraction more than 0.6). The boiling occurs at the heated section which is positioned at the center for vertically. Although the coolant is the liquid water at the inlet section of the fuel bundle, it changes water and vapor due to the boiling by fuel rods. The void fraction near wall region is lower than the center region in the radial direction because the heat transfer rate at the near wall region is lower than that at the center region.

In addition, predicted void fraction distributions in the radial direction are shown in Fig.10. Each predicted result on the radial void fraction distribution shown in Fig.11 is the result of 1/6 cross-section of a fuel bundle. At the vicinity of the boiling position near the channel inlet, the void fraction shows the highest at the narrowest region of adjacent fuel rods. On the other hand, at the vicinity of the channel outlet, it shows the highest at the center region surrounded by three fuel rods. That is, the bubble generated by boiling moves from the narrowest region of adjacent fuel rods to the center region surrounded by three fuel rods along the flow direction. This tendency is the same result as an experiment.

5 Conclusions

In order to predict the water-vapor two-phase flow dynamics in the RMWR fuel assembly and to reflect them to the thermal design of the RMWR core, large-scale three-dimensional boiling two-phase flow simulations were performed under the simulated fuel assembly condition. Water and vapor distributions around fuel rods and a spacer were clarified precisely. The present results were summarized as follows:

1) The fuel rod surface is encircled with thin water film;
2) The bridge formation by water film appears in the region where the gap spacing between adjacent fuel rods is narrow;
3) Vapor flows into the triangular region where the gap spacing between fuel rods is large.
4) A flow configuration of vapor shows a streak structure along the triangular region.
5) Boiling occurs at the narrowest region among the fuel rods at the vicinity of the start of the heated section, generated bubbles moves from the narrowest region to the center region among the fuel rods along the flow direction.

Acknowledgments

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Table 1　Parallelization performance of TPFIT

Number of CPUs	Parallelization efficiency	Execution performance	Execution efficiency	Calculation memory (GB)
128	100	49.6	6.05	136
256	87	88.9	5.42	165
512	81	173.1	5.28	260

Table 2　Parallelization performance of ACE-3D

Number of CPUs	Parallelization efficiency	Execution performance	Execution efficiency	Calculation memory (GB)
63	100	31.6	7.84	386
126	109	66.9	8.29	475
252	93	122.9	7.62	649

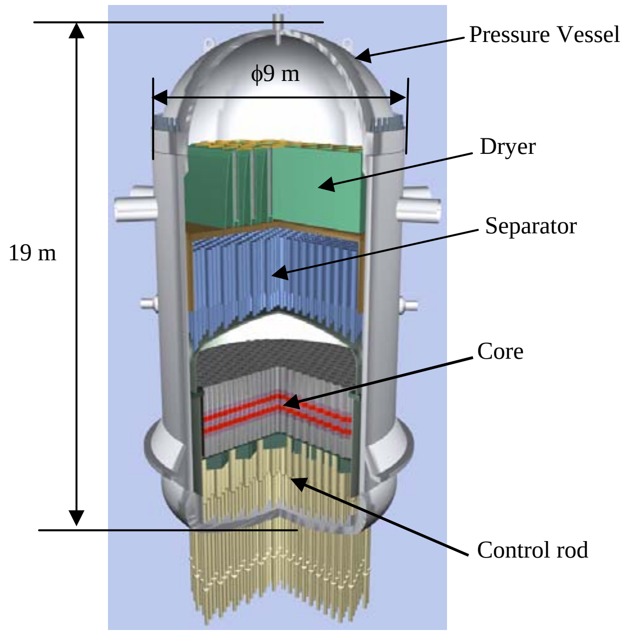


Fig.1　Outline of RMWR

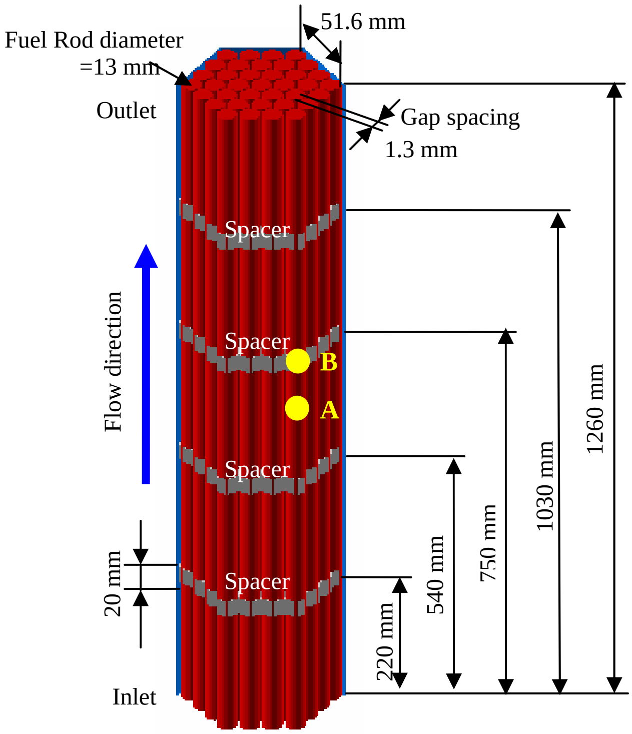
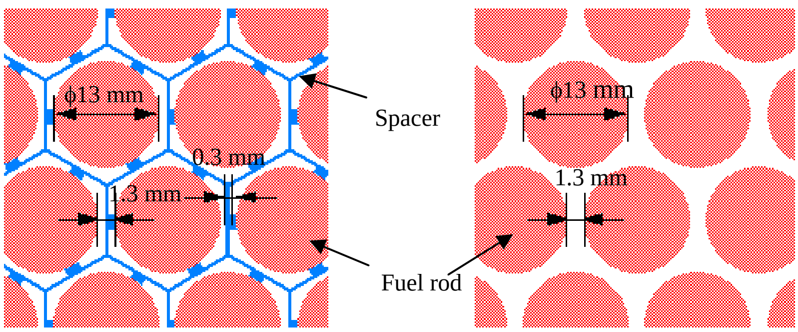


Fig.2 Analytical geometry of a tight-lattice fuel bundle



(a) Cross-section with a spacer

(b) Cross-section without a spacer

Fig.3 Cross-sectional views of the fuel bundle with and without a spacer

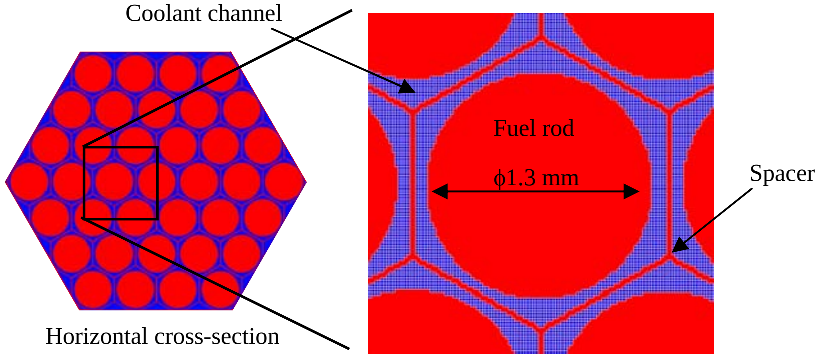


Fig.4　An example of calculation mesh division of TPFIT

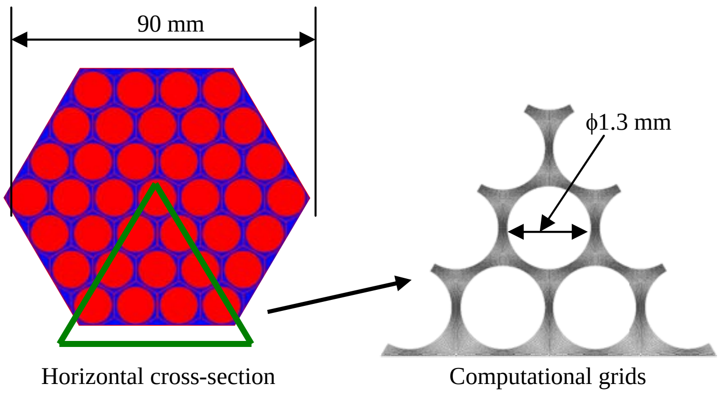


Fig.5　An example of calculation mesh division of ACE-3D

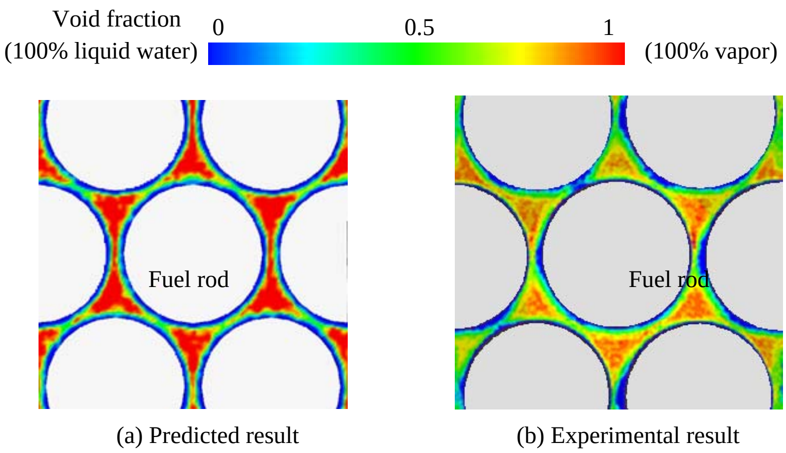
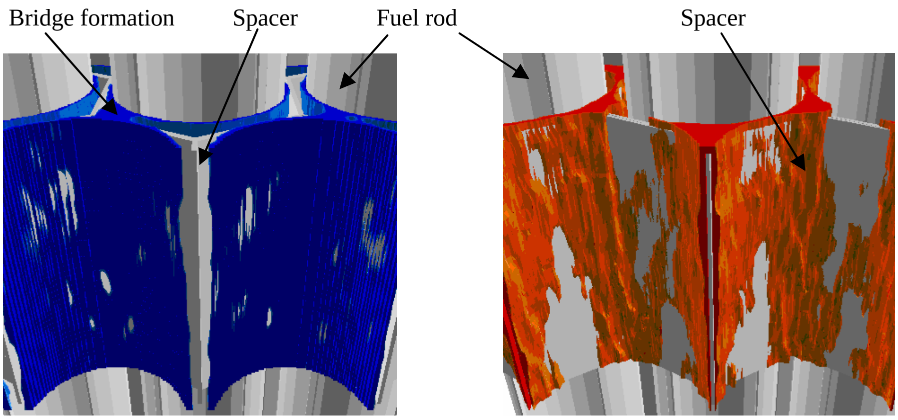


Fig.6　Comparison of predicted and measured void fraction distributions around fuel rods



(a) Predicted water distribution (Void fraction in blue is 0.1 or less)

(b) Predicted vapor distribution (Void fraction in red is 0.9 or more)

Fig.7 Predicted water and vapor distributions in the vertical direction around a spacer

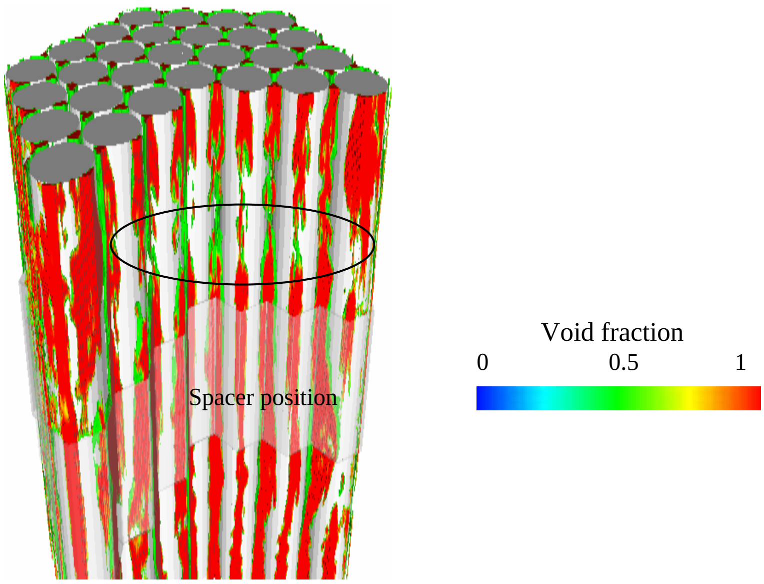


Fig.8 Predicted vapor structure around fuel rods: here, red indicates 100% non-liquid vapor and its void fraction is 1; then, green indicates an interface between water and vapor, and also its void fraction is 0.5.

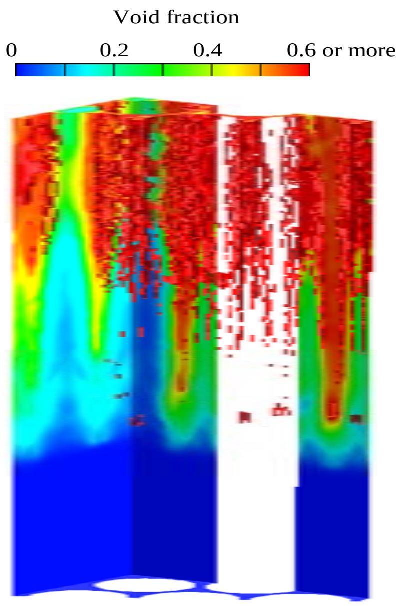


Fig.9　Predicted three-dimensional void fraction distribution in the axial direction

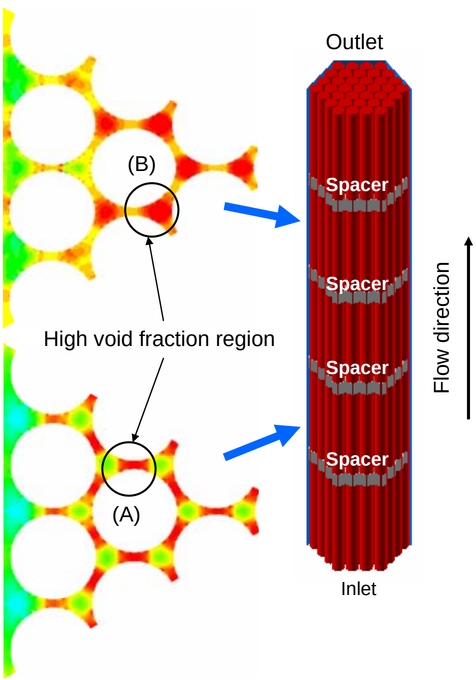


Fig.10　Predicted three-dimensional void fraction distribution in the radial direction