Article

A DNBR Analysis to Patterns of Subchannel Control Volume

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Abstract: The sensitivity of DNBR(Departure from Nucleate Boiling Ratio) values to approaches of subchannel control volume selection has been investigated for the TS01 and TS03 out of HIPER17 CHF(Critical Heat Flux) tests. In general, the coolant-centered subchannel method is applied to subchanel analyses for fuel bundle. When it comes to predicting for CHF of high quality region, however, the rod-centered subchannel method was better over high quality region. As a result, the rod-centered subchannel method were more suitable at a conservative point of view than the coolant-centered subchannel method comparing major properties. Also, it was confirmed that the radial subchannel locations at the minimum DNBR were similar when comparing both analysis results by two kind of methods.

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1. Introduction

The critical heat flux(CHF) test is an important procedure in developing the nuclear fuel for the pressurized water reactor(PWR). The high performance with efficiency and reliability(HIPER) fuel were developed by Korea Electric Power Corporation Nuclear Fuel(KEPCO NF). There are two types of lattice which are 16x16(HIPER16) and 17x17(HIPER17). Each HIPER fuel equipped structural spacer grids with mixing vanes to increase turbulent mixing within subchannels, hence enhance DNB performance. And the tests to verify the CHF correlations for two types of fuels are being performed at CEA(Commissariat à l'énergie atomique et aux énergies alternatives) in France. Several cases of many CHF test campaigns were chosen and verified to study the sensitivity of DNBR(Departure from Nucleate Boiling Ratio) values to approaches of subchannel control volume. The TS01 and TS03 campaigns out of HIPER17 CHF tests were analyzed for rod bundle CHF tests.

In rod bundle analysis, a subchannel approach is a special case of a generic porous media approach for a specific nodal layout. This nodal layout defines volumes of a size equivalent to a single fuel rod and its associated fluid. There are only two choice to formulate single subchannel, channel-centered and rod-centered. For a lumped channel, which grouping two or more subchannels upto whole assembly, it is a porous media approach. Most of the subchannel analyses used the coolant-centered subchannel nodal layout. But, it has been known that the rod-centered subchannel analysis showed good results for high quality critical heat flux [1,2]. Little additional systematic work has been accomplished on the development of the constitutive relations required for this rod-centered nodal layout. For mass velocity greater than 500 kg/ s $\cdot$ m^2, agreement is satisfactory and the error is only about 7% for the mass flux considered [3].

Various mechanistic models have been proposed so far [4,5]. Some of them predict successfully the DNB in rod bundles, however, the physical basis of these models still remains uncertain.

Weisman and Pei [6] proposed a DNB model, which illustrated the DNB as the bubble congestion to reach over a constant critical void fraction in a bubbly layer close to the heated wall.

In this model, the local void fraction was evaluated by a simple two-layer model, which could not provide reasonable void fraction at thermal non-equilibrium condition in a non-uniform power distribution [7].

In our study, it will be described that the results of the rod-centered subchannel analysis are compared to those of coolant-centered subchannel analysis with the DNBR value, the quality, and the mass velocity including the radial location of minimum DNBR. So, it will be determined which subchannel analysis is more efficient, effective, and conservative. The main objective is to suggest the appropriate subchannel approach between two methods for new CHF correlation development and its application for the advanced fuel with mixing vanes, and hence to support 3-dimensional safety analysis with detail rod-by-rod multiphysics frame.

2. Descriptions and Conditions

The OMEGA test facility at CEA Grenoble is a high pressure facility capable of simulating PWR bundle as 5x5 or 6x6 array fuel simulator with various heated length at PWR conditions of interest. The major loop components and their specifications are shown in Table 1. The 10 MW power supply (40kA @ 250 V DC) is equipped with a power regulation system that reduces the voltage and current fluctuation to a very low level. The loop is capable of operating with heater rods that could collapse at the high operating pressure. Therefore, a specific heater pressurization system was developed using 15 MPa nitrogen bottles. The geometrical characteristics of test bundle performed at OMEGA-2 facility in CEA are basically identical to reference CHF test facility, Heat Transfer Research Loop(HTRF) of Columbia University.

Table 1. Specification of the main OMEGA loop components

Main Component	Power (kW)	Maximum Admissible Temperature (℃)	Maximum Admissible Pressure (MPa)	Type
Power Supply	10,000	-	-	-
Primary Pump	193	352	19	Immersed rotor
Pressurizer	200	362	18	Vapor cover
Pre-heater	800	362	19.5	4 bodies
Coolant to air heat exchanger	Cooler1&2:5 Cooler 3:7	385	18.7	Finned tubes

It has a 5x5 typical cell, 9.5 mm of outside diameter heater rod, 12.6 mm of rod pitch and 3.0 m of heated length. The power distributions are radially non-uniform and axially uniform. The radial power factor of the outer 16 cold rods was approximately 82 percent of the inner 9 hot rods. The cold rods along the periphery were used to avoid CHF occurring near the non-typical wall. The desired radial power distribution was achieved by varying the overall tubing wall thickness among the rods. The rods which have high power are thick to draw more current for a given bus-to-bus voltage.

In rod bundle analysis, there are two subchannel control volume approaches. Figure 1(a) shows rod-centered subchannel nodal layout and Figure 1(b) shows coolant-centered subchannel nodal layout. In rod-centered subchannel, a single subchannel includes one entire rod as the center. In case of coolant-centered subchannel, a single subchannel includes a quarter by 4 rods but coolant as the center. Mostly, in rod bundle analysis, coolant-centered subchannel has been used. Further, one of major simplifications in the subchannel approach is the treatment of lateral exchanges between adjacent subchannels. It is assumed that any lateral flow through the gap region between subchannels loses its sense of direction after leaving the gap region. This allows subchannels to be connected arbitrarily since no fixed lateral coordinate is required. A fully three dimensional physical situation can be represented simply by connecting the channels in a three dimensional array. This leads to

simplifications in the lateral convective terms of the linear momentum balance equation that makes the most appropriate method for predominantly axial flow situations. The subchannel analysis approach and its associated boundary conditions are therefore not a fully three dimensional representation of the flow.
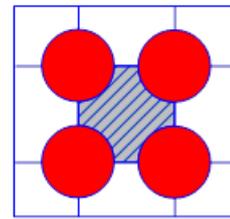

(a)   (b)

Figure 1. Patterns of subchannel control volume (a) Rod-centered subchannel; (b) Coolant-centered subchannel

In our study, using both approaches, the sensitivity of DNBR was investigated for TS01 and TS03. The geometry and subchannel nodal layout of calculation are shown in Figure 2 and Figure 3 for TS01 and TS03, respectively. Both TS01 and TS03 consist of 25 rods (5x5 array) and their rod radial powers for the tests are distributed more highly at the center. Axial rod lengths of them are 118.1 inches and their power distributions are uniform. And the rod diameter, rod pitch, rod-to-wall gap width are also shown in Figure 2 and Figure 3.
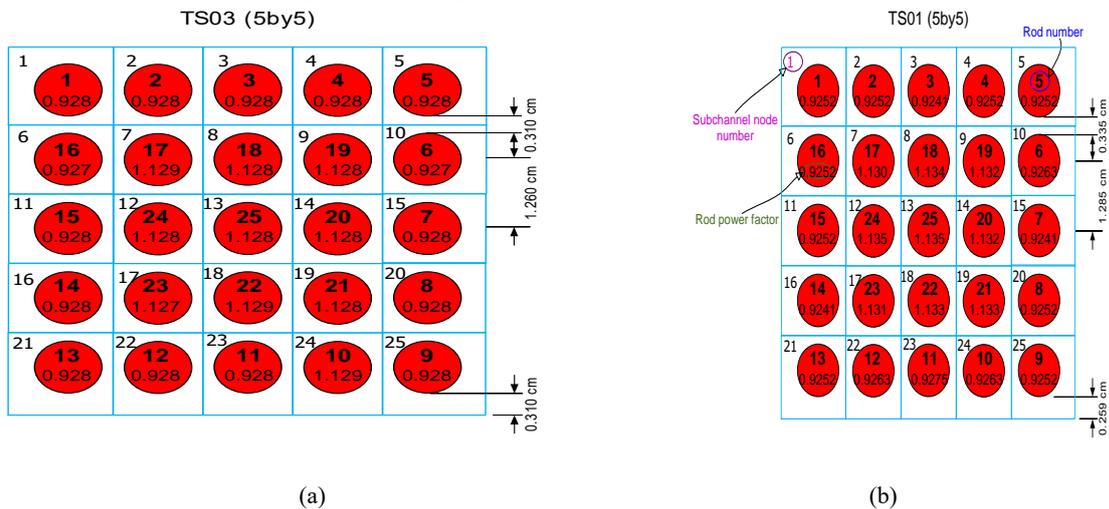
(a)   (b)

Figure 2. Geometry and subchannel nodal layout for TS01 (a) Rod-centered subchannel; (b) Coolant-centered subchannel
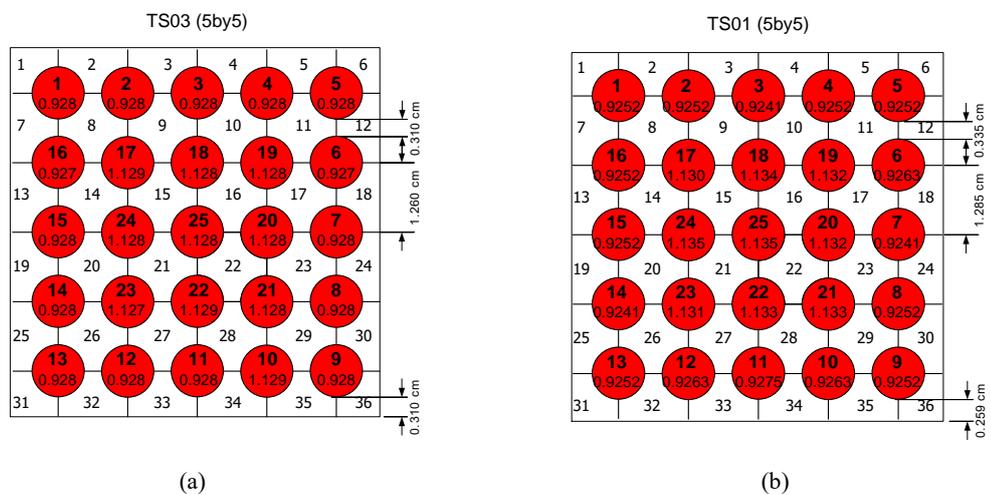
(a)   (b)

Figure 3. Geometry and subchannel nodal layout for TS03 (a) Rod-centered subchannel; (b) Coolant-centered subchannel

The number of subchannel nodes is 25 for rod-centered subchannel and 36 for coolant-centered subchannel. The conditions for calculation are listed in Table 2. Flow area, wetted perimeter, heated

perimeter, and gap width between subchannel nodes are compared with control volume approach for TS01 and TS03 shown as Table 3 and Table 4. The flow area of rod-centered approach is greater than that of coolant-centered approach. Its values are 69~228% above that of coolant-centered approach for corner and side types. This is resulted in more heat transfer rate per one subchannel node. The wetted perimeter of rod-centered approach is greater than that of coolant-centered approach. Its values are 54~159% above that of coolant-centered approach for corner and side types. This is resulted in more pressure loss per one subchannel node.

Table 2. Parameters spectrum for calculation

Parameter	TS01	TS03
Pressure (MPa)	9.48~16.59	10.46~16.6
Inlet temperature (℃)	137.22~334.11	86.72~324.61
Mass velocity, G (kg/s·m²)	1006.3~4768.5	1017.2~4871.6
Average heat flux (MW/m²)	1.3748~2.9006	1.6085~3.4196

Table 3. Geometric data for rod-centered and coolant-centered subchannel for TS01

Rod-to-wall gap width (cm)	Subch. type	Area (cm²)	Wetted perimeter (cm)	Heated perimeter (cm)	Gap width (cm)
0.2591 (rod centered)	Corner	1.1865	5.7377	2.9844	1.3767
	Side	1.0606	4.2696	2.9844	1.3767, 1.2852
	Center	0.9431	2.9844	2.9844	1.2852
0.2591 (coolant centered)	Corner	0.3617	2.2142	0.7461	0.2591
	Side	0.5891	2.7774	1.4922	0.2591, 0.3353
	Center	0.9431	2.9844	2.9844	0.3353

Table 4. Geometric data for rod-centered and coolant-centered subchannel for TS03

Rod-to-wall gap width (cm)	Subch. type	Area (cm²)	Wetted perimeter (cm)	Heated perimeter (cm)	Gap width (cm)
0.3099 (rod centered)	Corner	1.2928	5.8139	2.9844	1.4148
	Side	1.0736	4.2442	2.9844	1.4148, 1.2598
	Center	0.8784	2.9844	2.9844	1.2598
0.3099 (coolant centered)	Corner	0.4388	2.3158	0.7461	0.3099
	Side	0.6344	2.7520	1.4922	0.3099
	Center	0.8784	2.9844	2.9844	0.3099

The code used in rod bundle analysis is THALES [4] and its CHF correlation is an applicable correlation. The applicable range of CHF correlation for TS01 and TS03 is shown in Table 5. Grid spacing, fuel active length, rod pitch, and rod outer diameter are met with correlation data base.

Table 5. Geometric data for rod-centered and coolant-centered subchannel for TS03

Parameter	Correlation DB (Applicable range)	TS01/TS03	Remark
Mixing vane	RTSV	←	same
Grid spacing (cm)	25.4 ~ 66.04	39.88/25.4	within range
Fuel active length (cm)	~ 426.72	300.0	within range
Fuel rod pitch (cm)	1.232 ~ 1.328	1.285/1.260	within range
Fuel rod O.D. (cm)	0.914 ~ 1.031	0.950	within range
Lattice array	square	←	same

3. Comparison of Results

Figure 4 shows the variation of M/P(Measured critical heat flux / Predicted critical heat flux) with quality for TS01 and TS03. M/P provides some information how well CHF correlation predicts CHF while retaining the conservatism. In general, it is a conservative result when the prediction by CHF correlation is lower than measured CHF. The quality of rod-centered subchannel is a little bit higher than that of coolant-centered subchannel. Because the heat transfer rate of rod-centered subchannel which has a larger flow area predicts higher than that of coolant-centered subchannel.
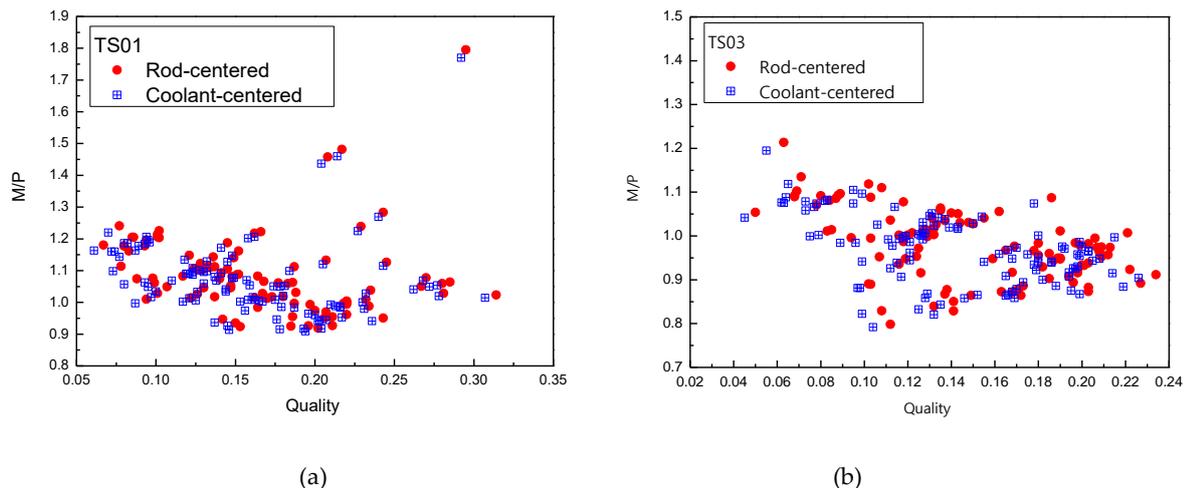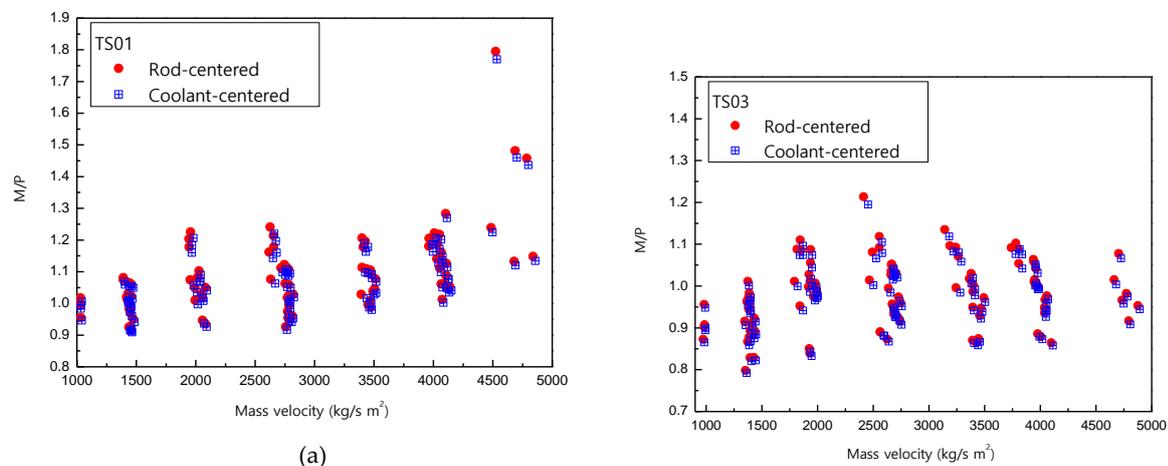

(a)   (b)

Figure 4. Variation of M/P with quality (a) TS01; (b) TS03

(a)

(b)

Figure 5. Variation of M/P with mass velocity (a) TS01; (b) TS03

Figure 5 shows the variation of M/P with mass velocity for TS01 and TS03. Mass velocity of rod-centered subchannel is lower than that of coolant-centered subchannel. The higher quality of rod-centered subchannel has the lower density and this relates the lower mass velocity. Figure 6 shows the variation of M/P with pressure for TS01 and TS03. When the results are compared, M/P of rod-centered subchannel is a little bit higher than that of coolant-centered subchannel at the same pressure. It is concluded that the result of rod-centered subchannel is more conservative than that of coolant-centered subchannel due to higher quality. The averaged M/P of TS01 is 1.085 and 1.072 for rod-centered and coolant-centered, respectively. Its deviation is 12.1%. The averaged M/P of TS03 is 0.976 and 0.969 for rod-centered and coolant-centered, respectively. Its deviation is 7.2%.
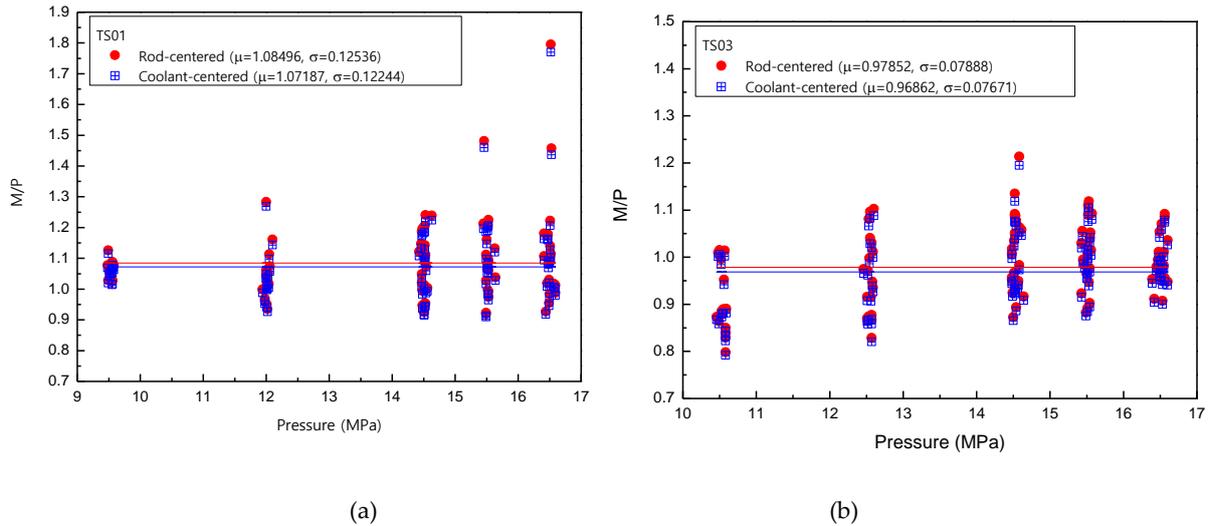

Figure 6. Variation of M/P with pressure (a) TS01; (b) TS03

Figure 7 shows the comparison of M/P with each subchannel control volume for TS01 and TS03. Both cases show that the M/P with rod-centered subchannel is a little bit higher than that with coolant-centered subchannel. As mentioned in Figure 6, also, the results of rod-centered subchannel are more conservative than those with coolant-centered subchannel in a point of view of DNBR.
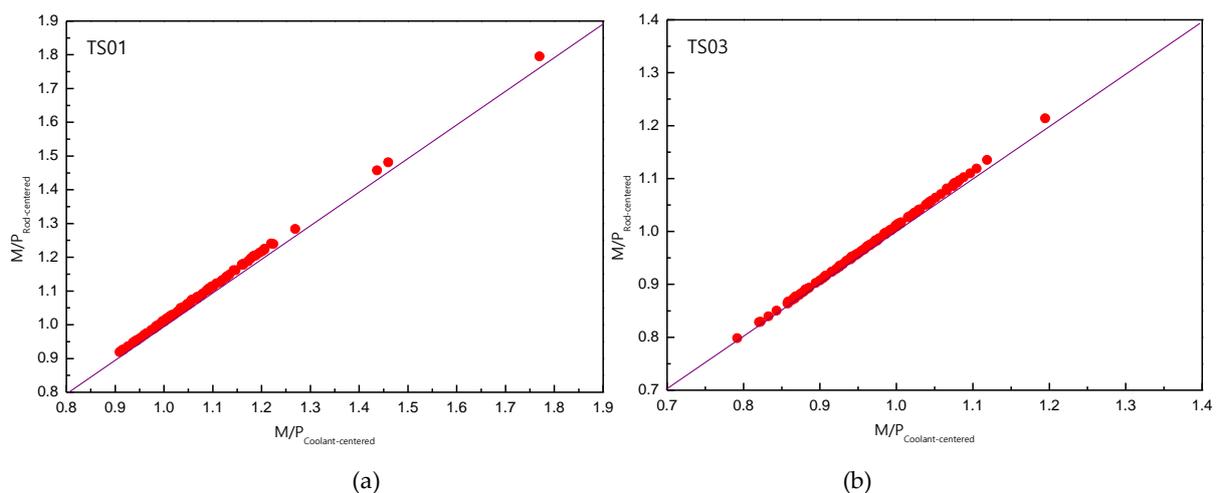

Figure 7. Comparision of M/P (a) TS01; (b) TS03

Figure 8 and 9 show the location of MDNBR with each subchannel control volume for TS01 and TS03. The radial location at which minimum DNBR occurs is 13th subchannel node for rod-centered approach and 22th node for coolant-centered approach.
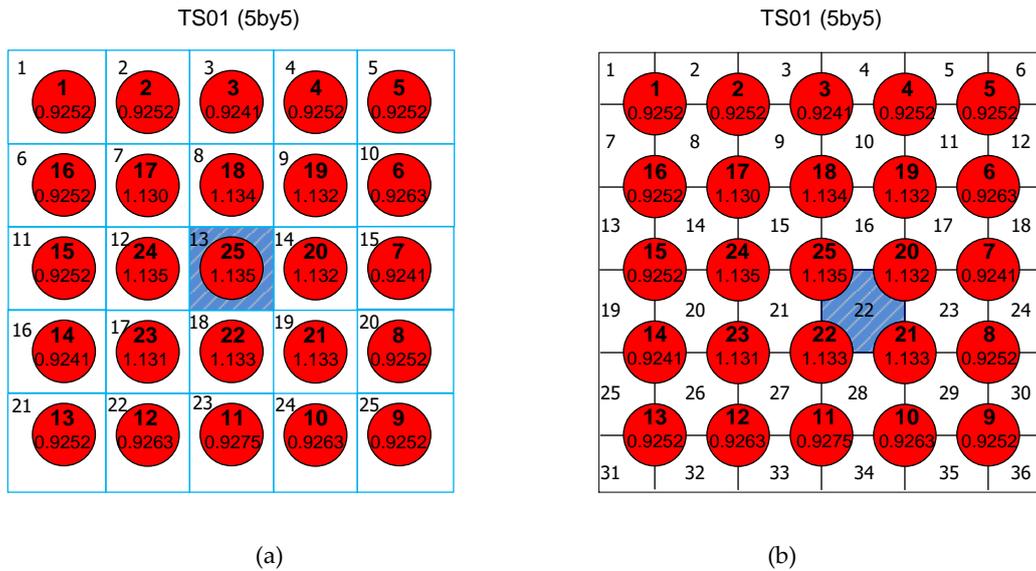
(a)   (b)

Figure 8. Locations of MDNBR for TS01 (a) Rod-centered subchannel; (b) Coolant-centered subchannel

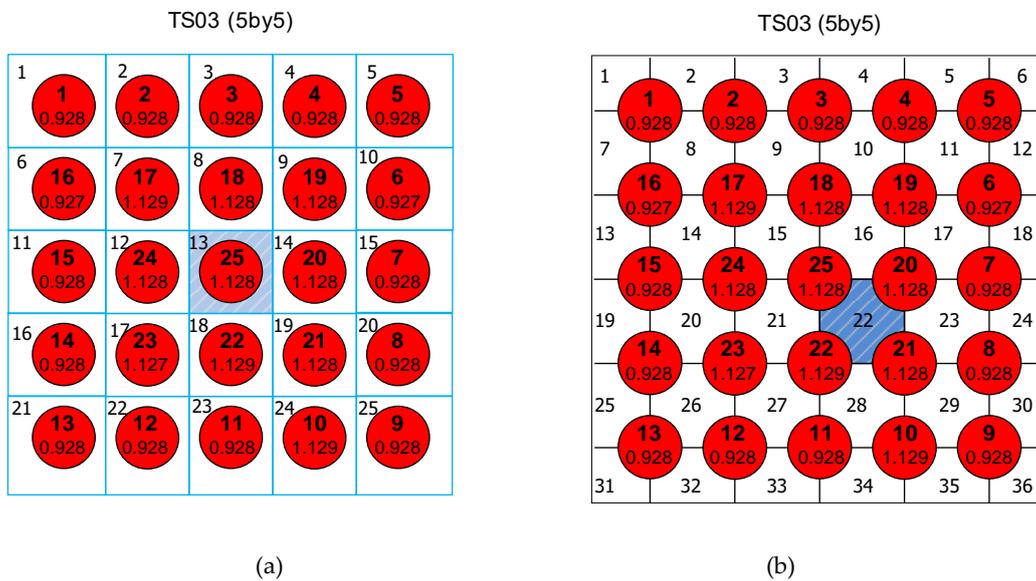(a)   (b)

Figure 9. Locations of MDNBR for TS03 (a) Rod-centered subchannel; (b) Coolant-centered subchannel

The locations at which minimum DNBR occurs are very adjacent. Figure 10 and 11 show probability density functions of M/P with each subchannel control volume for TS01 and TS03.
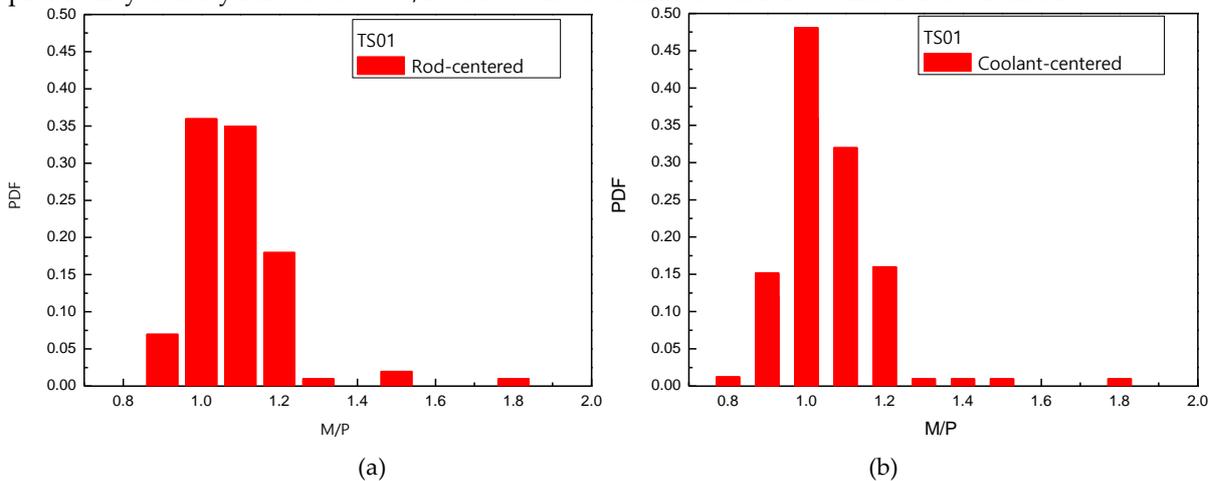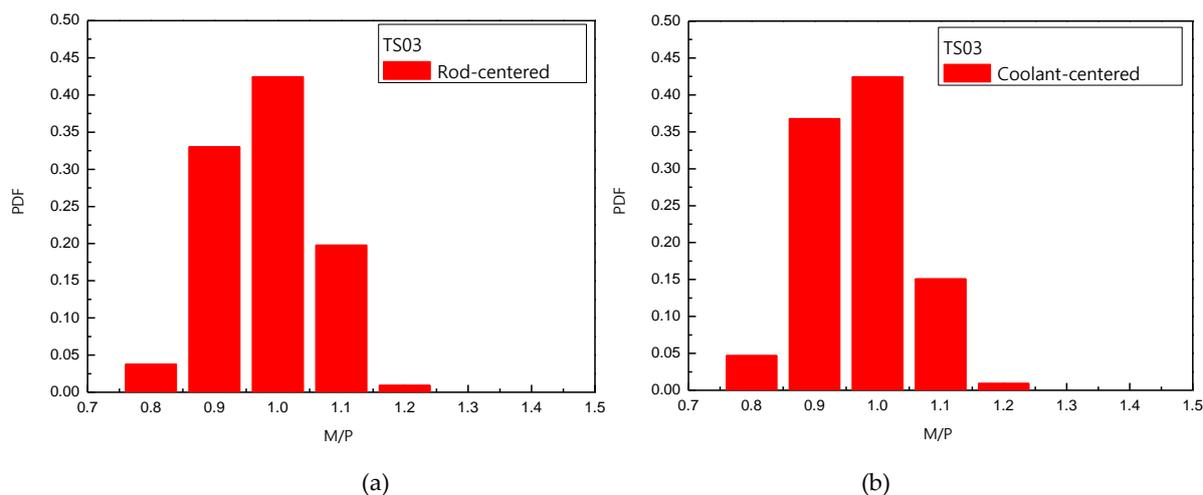

(a)   (b)

Figure 10. Probability density function of M/P for TS01 (a) Rod-centered subchannel; (b) Coolant-centered subchannel

(a) (b)

Figure 11. Probability density function of M/P for TS03 (a) Rod-centered subchannel; (b) Coolant-centered subchannel

4. Conclusions

In subchannel analysis with rod bundle at nuclear power plant, two methods of rod-centered method and coolant-centered method exist traditionally. There is no method other than current two-methods in subchannel analysis using lumped nodes, unlike computational fluid dynamics(CFD) analysis, which simulates a real geometry. By comparing the results using THALES subchannel code with two methods, it was confirmed that rod-centered method used currently for core thermal-hydraulic design is still valid. The differences between other subchannel codes were not found with their results.

The results with rod-centered subchannel are more conservative than those with coolant-centered subchannel in a point of view of DNBR. The radial subchannel locations at the minimum DNBR occurs are similar. So, rod-centered subchannel control volume analysis is more efficient with for CHF tests with HIPER16 and HIPER17 fuel. This reliable rod-centered approach will be considered as an alternative to the more rigorous approach used for CHF prediction in a rod bundle. Therefore, it is recommended that the rod-centered approach is applicable for the next CHF correlation development with new fuel.

Also, the sensitivity of transverse momentum parameter was investigated, but its effect was not so much to DNBR for very high mass velocity. The each subchannel can be considered separately without considering the effects of its radially adjacent subchannels.

Conflicts of Interest: The authors declare no conflict of interest.

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