Development of Hybrid Core Calculation System Using 2-D Full-core Heterogeneous Transport Calculation And 3-D Advanced Nodal Calculation

Masaaki Mori[*1], Naoki Sugimura[1], Masayuki Hijiya[1], Tadashi Ushio[1], and Yasushi Arakawa[2]

[1]*Nuclear Engineering, Limited (NEL),*

1-3-7 Tosabori Nishi-ku, Osaka 550-0001, Japan

[2]*The Kansai Electric Power Co., Inc.,*

3-3-22, Nakanoshima, Kita-Ku, Osaka, 530-8270, Japan

This paper presents the Hybrid Core Calculation System which is a very rigorous but a practical calculation system applicable to best estimate core design calculations taking advantage of the recent remarkable progress of computers. The basic idea of this system is to generate the correction factors for assembly homogenized cross sections, discontinuity factors, etc. by comparing the CASMO-4 and SIMULATE-3 2-D core calculation results under the consistent calculation condition and then apply them for SIMULATE-3 3-D calculation. The CASMO-4 2-D heterogeneous core calculation is performed for each depletion step with the core conditions previously determined by ordinary SIMULATE-3 core calculation to avoid time consuming iterative calculations searching for the critical boron concentrations while treating the thermal hydraulic feedback. The final SIMULATE-3 3-D calculation using the correction factors is performed with iterative calculations searching for the critical boron concentrations while treating the thermal hydraulic feedback.

KEYWORDS: hybrid, MOC, CASMO-4, full-core, heterogeneous, transport calculation, SIMULATE-3

1. Introduction

It is important to enhance the accuracy of core design calculations and to enable the best estimate core design to enhance the economy of nuclear power plants. Thanks to the recent remarkable progress of computers, three-dimensional (3-D) heterogeneous transport core calculations based on such as continuous energy Monte Carlo or method of characteristics (MOC) are going to be put into practical use in the near future. [1-3] However, the application of such calculation would be limited to some benchmarking

*Corresponding author, Tel. +81-6-6446-9361, FAX +81-6-6446-1746, E-mail: mmori@neltd.co.jp

purpose of design codes or analysis of zero power condition in a first loading core, whose condition is not affected by fuel temperature distributions, water density distributions, etc.

To simulate the core in its operating state, it is necessary to iterate alternately neutronics and thermal hydraulic calculations, to take account the influences of the fuel temperature distributions, water density distributions, etc. upon the fuel cross sections (feedback effect). Moreover, for a PWR case, iterative calculations searching for the critical boron concentration should be required for every core depletion step. Therefore, 3-D heterogeneous transport core calculation for a practical core design would be extremely time consuming and not feasible in the near future. Especially, as for continuous energy Monte Carlo calculation, it is almost impossible to obtain the satisfactory small statistical uncertainty of local pin power distribution, which is acceptable for actual core design calculations to assure the safety of the core. Even for the deterministic 3-D heterogeneous transport core calculation such as MOC, the application to an online core monitoring calculation at an on-site computer, which requires a high speed calculation, or to a time-dependent kinetic calculation of a core is not practical and feasible.

According to the generalized equivalence theory, it is possible to reproduce the calculation results of a heterogeneous core calculation by a nodal core calculation provided with the assembly homogenized cross sections and flux discontinuity factors at assembly interfaces obtained from the heterogeneous core calculation. [4] However, heterogeneous core calculation has been too time consuming and advanced nodal codes such as SIMULATE-3 usually use homogenized assembly cross sections and discontinuity factors calculated by single assembly calculations by means of two-dimensional (2-D) heterogeneous transport calculation codes such as CASMO-4. [5,6] This is an approximated but a practical approach that assumes reflective boundary conditions at the assembly surfaces and the validity of this approximation has been demonstrated intensively.

Taking advantage of the remarkable progress of computers, recent extensions of CASMO-4 have been made to permit direct 2-D transport calculation in exact 2-D heterogeneous full core geometry using the method of characteristics (MOC) provided with non-linear diffusion acceleration technique. [7] The transport calculation can be performed with the same spatial and angular detail applied to single-assembly analysis. It is also capable for performing core depletion calculation and treating the actual full scope fuel shuffling and shutdown cooling during the core outage.

Although it is a very rigorous and powerful code for the purpose of benchmarking of core design calculation codes, it can not be directly applied to actual core design calculations since CASMO-4 itself can not treat the effect of axial distribution of fuel and moderator temperature or fuel exposure. It would also be too time consuming to perform iterative calculations searching for the critical boron concentrations while treating the thermal hydraulic feedback inside CASMO-4 itself. In order to realize an actual core design calculation method with ultimate calculation precision equivalent to a heterogeneous core calculation, Nuclear Engineering, Limited(NEL) has developed the Hybrid Core Calculation System using CASMO-4 2-D full-core heterogeneous transport calculation and SIMULATE-3 3-D advanced nodal calculation with the support of Studsvik Scandpower.

2. Calculation method

The basic idea of this system is to generate the correction factors for assembly homogenized cross sections, discontinuity factors, etc. by comparing the CASMO-4 and SIMULATE-3 2-D core calculation results under the consistent calculation condition and then apply them for SIMULATE-3 3-D calculation. The CASMO-4 2-D heterogeneous core calculation is performed for each depletion step with the core conditions previously determined by ordinary SIMULATE-3 core calculation to avoid time consuming iterative calculations searching for the critical boron concentrations while treating the thermal hydraulic feedback. The final SIMULATE-3 3-D calculation using the correction factors is performed with iterative calculations searching for the critical boron concentrations while treating the thermal hydraulic feedback.

This system is expected to be as accurate as 3-D heterogeneous multi-group transport core calculation but much faster than such full-scope 3-D transport core calculation. The Hybrid Core Calculation System comprises procedure of the following steps:

2.1 Step-1: Determination of 2-D core calculation conditions

Perform SIMULATE-3 advanced nodal core calculation using the standard assembly homogenized cross sections, discontinuity factors generated by the CASMO-4 single assembly calculations. The boron concentration and fuel and moderator temperature distribution are determined by this calculation for each depletion step.

2.2 Step-2: Generation of Correction factors

Here, the correction factors for assembly homogenized cross sections, discontinuity factors, etc. are generated by comparing the CASMO-4 and SIMULATE-3 2-D core calculation results under the consistent calculation condition in the following procedure:

2.2.1 Step 2-1: CASMO-4 2-D heterogeneous core calculation

Step 2-1 CASMO-4 2-D heterogeneous core calculation is performed with the consistent conditions based on the boron concentration and fuel and moderator temperature distributions calculated by the above Step-1 SIMULATE-3 core calculation for each depletion step. Here, CASMO-4 computes the following parameters:

XS_{C2D} : Assembly homogenized cross sections by CASMO-4 2-D core calculation
DF_{C2D} : Discontinuity factors by CASMO-4 2-D core calculation
PP_{C2D} : Pin power distributions by CASMO-4 2-D core calculation
DR_{C2D} : Detector response by CASMO-4 2-D core calculation

Since this CASMO-4 2-D heterogeneous core calculation is performed for each depletion step with the core conditions determined by the Step-1 SIMULATE-3 core calculation, we need not perform time consuming iterative calculations searching for the critical boron concentrations while treating the thermal hydraulic feedback.

2.2.2 Step 2-2: SIMULATE-3 2-D homogeneous core calculation

SIMULATE-3 2-D homogeneous core calculation is performed with the core conditions calculated by the Step-1 SIMULATE-3 core calculation for each depletion step, which is consistent with Step 2-1 CASMO-4 2-D heterogeneous core calculation. In this Step 2-2 SIMULATE-3 2-D homogeneous core calculation, the original assembly homogenized cross sections XS_{S2D} and assembly discontinuity factors DF_{S2D} are replaced with the exact parameters XS_{C2D} and DF_{C2D} calculated by the Step 2-1 CASMO-4 2-D core calculation.

In this step, the correction factors for assembly homogenized cross sections and discontinuity factors are generated by comparing the CASMO-4 exact parameters and corresponding interpolated parameters based on CASMO-4 single assembly calculations for SIMULATE-3 2-D core calculation as follows:

$$CXS = XS_{C2D} / XS_{S2D}$$
$$CDF = DF_{C2D} / DF_{S2D}$$

Note that XS_{S2D} and DF_{S2D} are interpolated and corrected values, which were going to be used for SIMULATE-3 2-D core calculation, for the given boron concentration, fuel and moderator temperature distribution, etc from the pre-tabulated assembly two-group constants based on CASMO-4 single assembly calculations.

Given with the exact XS_{C2D} and DF_{C2D}, SIMULATE-3 2-D homogeneous core calculation can reproduce the global core characteristics by Step 2-1 CASMO-4 2-D core calculation in exact 2-D heterogeneous full core geometry. However, the detailed pin-wise calculation results of the Step 2-1 CASMO-4 2-D core calculation can not be reproduced since SIMULATE-3 calculation uses the form functions based on CASMO-4 single assembly calculations. In order to eliminate this error, the correction factors for pin power distributions and detector response are generated as follows:

$CPP = PP_{C2D} / PP_{S2D}$
$CDR = DR_{C2D} / DR_{S2D}$

where,
PP_{S2D} : Pin power distributions by SIMULATE-3 2-D core calculation
DR_{S2D} : Detector response by SIMULATE-3 2-D core calculation

Note that PP_{S2D} and DR_{S2D} are SIMULATE-3 2-D core calculation results using the exact XS_{C2D} and DF_{C2D} by Step 2-1 CASMO-4 2-D core calculation and the form functions for intra-assembly pin power distributions and detector response. All the form functions used in the pin power reconstruction method to compute PP_{S2D} and DR_{S2D} in SIMULATE-3 2-D core calculation are interpolated and corrected values for the given boron concentration, fuel and moderator temperature distribution, etc from the pre-tabulated assembly two-group constants based on CASMO-4 single assembly calculations.

2.3 Step-3: SIMULATE-3 3-D core calculation using the correction factors

With use of the correction factors obtained through the above procedure, the Step-3 SIMULATE-3 3-D core calculation is then executed to get the final calculation results. The corrections are applied in the following procedures:

Three-dimensional nodal core calculation is performed using the assembly homogenized cross sections and discontinuity factors multiplied by the correction factors CXS and CDF as follows:

XS_{S3D} (corrected) = CXS * XS_{S3D}
DF_{S3D} (corrected) = CDF * DF_{S3D}

where,
XS_{S3D} : Assembly homogenized cross sections for SIMULATE-3 3-D core calculation
DF_{S3D} : Discontinuity factors for SIMULATE-3 3-D core calculation

These corrections using CXS and CDF are made after all the interpolations and corrections for every iteration for critical boron concentration and the thermal hydraulic feedback. The pin power distributions and detector response based on the pin power reconstruction method are computed after the above 3-D nodal core calculation and then they are multiplied by the correction factors CPP and CDR as follows:

PP_{S3D} (corrected) = CPP * PP_{S3D}
DR_{S3D} (corrected) = CDR * DR_{S3D}

where,
PP_{S3D} : Pin power distributions by SIMULATE-3 3-D core calculation
DR_{S3D} : Detector response by SIMULATE-3 3-D core calculation

Note that all the form functions used in the pin power reconstruction method to compute PP_{S3D} and DR_{S3D} in SIMULATE-3 3-D core calculation are interpolated and corrected values for the boron concentration, fuel and moderator temperature distribution, etc obtained by the converged 3-D nodal calculation above.

Using the correction factors obtained from the Step-2 2-D heterogeneous and 2-D homogeneous nodal core calculations in Step-3 SIMULATE-3 3-D core calculation, it is possible to obtain comparable calculation precision to that of a 3-D heterogeneous core calculation. This system requires much shorter calculation time and smaller computer memory than those required by a full scope 3-D heterogeneous core calculation. Furthermore, by performing the 2-D heterogeneous core calculation based on critical boron concentration, in-core temperature distributions, etc. determined by the Step-1 SIMULATE-3 core calculation, it is possible to avoid iteration of the time consuming CASMO-4 heterogeneous core calculation.

3. Verification

The Hybrid Core Calculation System was verified against a 3411MWth Westinghouse-Type Japanese 4-loop PWR with 193 fuel assemblies. Figures 1 and 2 show comparison results of the calculated and measured radial reaction rate distribution by MD system at HFP condition for example. Although the original CASMO-4/SIMULATE-3 results are considerably accurate, the Hybrid Core Calculation System gives even more accurate results.

4. Conclusion

The Hybrid Core Calculation System is a very rigorous but a practical calculation system applicable to best estimate core design calculations taking advantage of the recent remarkable progress of computers. The concept of this system is very effective for accurate 3-D core simulations without increasing the execution times once given the correction factors.

This system is basically very flexible to the future progress of computers; 2-D heterogeneous core calculation can be performed for multiple planes of the core to treat axial blanket fuel assemblies or more detailed axial effects of burnup and temperature distributions.

The Hybrid Core Calculation System would be especially advantageous for radially heterogeneous cores such as MOX loaded cores. Given with the correction factors, this system is also effective for the application to high-speed core calculations for online core monitoring calculations at on-site computers or to time-dependent kinetic core calculations such as real time simulator.

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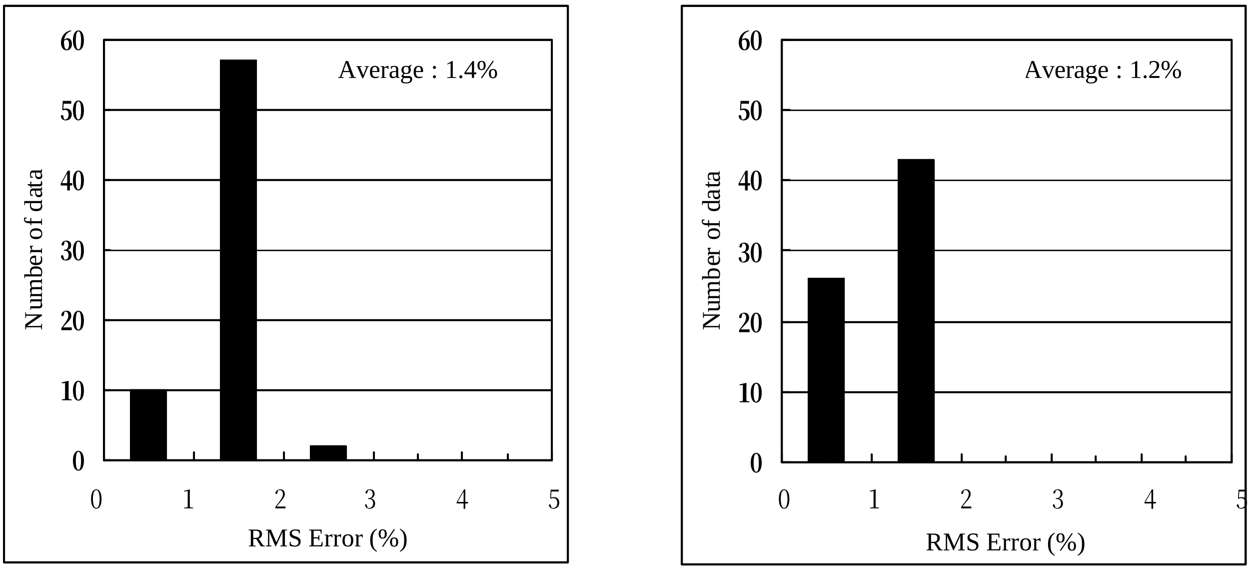
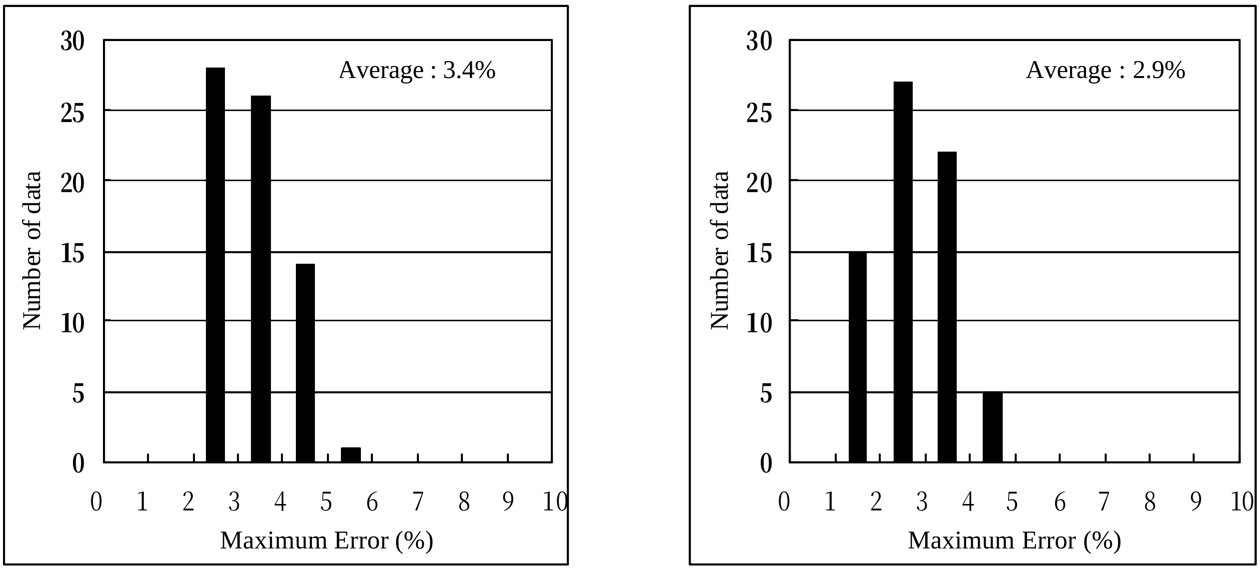


Original CASMO-4/SIMULATE-3 **Hybrid Core Calculation System**

Note : Error of calculated radial reaction rate = (Meas. - Calc.) / Calc.

Fig. 1 Histogram of the RMS error of calculated radial reaction rate distribution



Original CASMO-4/SIMULATE-3 **Hybrid Core Calculation System**

Note : Error of calculated radial reaction rate = (Meas. - Calc.) / Calc.

Fig. 2 Histogram of the maximum error of calculated radial reaction rate distribution