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Development of an Optimization Technique of CETOP-D Inlet Flow Factor for Reactor Core Thermal Margin Improvement

Sung Deok Hong, Jong Seon Lim, Yeon Jong Yoo, Jung Tack Kwon, and Jong Ryul Park
Korea Atomic Energy Research Institute
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원자로심의 열적여유도 증대를 위한 CETOP-D의 입구유량인자 최적화 기법 개발

홍성덕 · 임종선 · 유연종 · 권정택 · 박종률
한국원자력연구소
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Abstract

The recent ABB/CE(Asea Brown Boveri Combustion Engineering) type pressurized water reactor s have the on-line monitoring system, i.e., the COLSS(core operating limit supervisory system), to prevent the specified acceptable fuel design limits from being violated during normal operation and anticipated operational occurrences. One of the main functions of COLSS is the on-line monitoring of the DNB(departure from nucleate boiling) overpower margin by calculating the MDNBR(minimum DNB ratio) for the measured operating condition at every second. The CETOP-D model, used in the MDNBR calculation of COLSS, is benchmarked conservatively against the TORC model using an inlet flow factor of hot assembly in CETOP-D as an adjustment factor for TORC.

In this study, a technique to optimize the CETOP-D inlet flow factor has been developed by eliminating the excessive conservatism in the ABB/CE's. A correlation is introduced to account for the actual variation of the CETOP-D inlet flow factor within the core operating limits. This technique was applied to the core operating range of the YongGwang Units 3&4 Cycle 1, which results in the increase of 2% in the DNB overpower margin at the normal operating condition, compared with that from the ABB/CE method.

요 약

근래의 ABB/CE형 가압경수로들은, 정상운전 및 예상운전과도상태 중에 허용핵연료설계제한치가 위배되는 것을 방지하기 위하여, 노심운전상태를 감시하는 디지탈노심감시계통, COLSS(Core Operating Limit Supervisory System)를 보유하고있다. COLSS의 주요 기능 중 하나는, 측정되는 운전조

건에 대한 최소 핵비등이탈률을 계산하여, 핵비등이탈에 대한 과출력여유도를 감시하는 것이다. COLSS에서 최소 핵비등이탈률을 계산하는데 사용되는 CETOP-D 모델은 상세부수로분석코드인 TORC 모델에 대해 보수적으로 벤치마킹되며, 보정상수로서 고온집합체의 입구유량인자를 사용하고 있다. 본 연구에서는 CETOP-D 입구유량인자를 가장 제한적인 운전조건에서 보수적인 단일 값으로 결정하는 ABB/CE 방법을 배제하고, 운전조건에 따른 CETOP-D 입구유량인자 변화를 상관식형태로 결정하는 "CETOP-D 입구유량인자 최적화 기법"을 개발하였다. 개발된 방법을 영광 3,4호기 초기노심의 노심운전영역에 적용한 결과, 기존의 ABB/CE 방법에 비하여 정상운전영역에서 핵비등이탈에 대한 과출력여유도가 2% 가량 증가하였다.

1. Introduction

The PWRs(pressurized water reactors) shall be designed with a sufficient thermal margin to the SAFDLs(specified acceptable fuel design limits) to assure that they are operated safely within the LCOs(limiting conditions for operation). The recent ABB/CE (Asea Brown Boveri Combustion Engineering) type PWRs have the on-line monitoring and protection systems, i.e., the COLSS/CPCs(core operating limit supervisory system/core protection calculators), to prevent SAFDL from being violated during normal operation and AOOs(anticipated operational occurrences).

One of the main functions of COLSS is the on-line monitoring of the DNB (departure from nucleate boiling) overpower margin using the CETOP-D model which calculates the MDNBR(minimum DNB ratio) for the measured operating condition. the COLSS needs a sufficient thermal margin to keep the full power operation of a reactor core safe. Thermal margin could be determined by the smaller of the DNB-OPM(DNB overpower margin) and the LHR-OPM(linear heat rate overpower margin). Most of ABB/CE type PWRs are DNB limiting reactors. So, the CETOP-D model which calculates MDNBR and DNB-OPM in COLSS/CPCs is called "thermal margin model". Meanwhile, the gain in the sufficient thermal margin may relax the operating space of the core, reduce the fuel cycle cost and, extend the plant cycle length[1].

The MDNBR which serves as a measure for the DNB-OPM of the core can be predicted by the TORC code[2] at design stage. A multi-stage TORC model which produces a detailed three-dimensional description of the core thermal-hydraulics requires much central processing time for each steady-state MDNBR calculation. This means that the TORC model is not appropriate for the analysis which requires many MDNBR calculations, and also implies that it is inadequate to use it in the on-line systems such as COLSS/CPCs. Therefore, ABB-CE has developed the CETOP-D model, which calculates the MDNBR based on a four-channel core representation[3, 4], to reduce the central processing time for each MDNBR calculation. The comparison of TORC model with CETOP-D model is presented in Table 1.

Such a simplified CETOP-D model requires an adjustment factor, CIF(CETOP-D Inlet flow Factor) of the hot assembly, to eliminate the possible non-conservatism in the MDNBR. Hence, the CETOP-D model is benchmarked against the TORC model to seek the minimum CIF which will produce the conservative result of the MDNBR. The CIF should

Table 1. Comparison of TORC Model with CETOP-D Model

Item	TORC	CETOP-D
Usage	Design(off-line)	COLSS/CPCs(on-line)
Numerical method	Iteration	Prediction-Correction
Channel No.	120	4
Run Time	200 sec.	0.2 sec.
Adjustment factor	N/A	CIF

satisfy the following benchmarking criterion[5] within the core operating limits of the core.

$$MDNBR_{TORC} \geq MDNBR_{CETOP\text{-}D} \quad (1)$$

The benchmarked CETOP-D model is used in the DNB-OPM calculation of COLSS. The COLSS generates the MDNBR of the core at every second and displays the MDNBR information to the operator.

The current method of the DNB-OPM calculation uses the conservative CIF that satisfies the benchmarking criterion over the entire operating range of the core. But the actual CIF varies according to the variation of the operating conditions of the core. This means that some DNB-OPM is lost at other conditions due to the use of the minimum inlet flow factor. For example, the loss of DNB-OPM by the ABB/CE method[5] is about 4% in power at the normal operating condition for the YongGwang Units 3&4 Cycle 1. Figure 1 represents the conceptional plot between the minimum CIF at the worst operating condition of the core and the CIF curve at the other operating space. Therefore, the DNB-OPM of the ABB/CE type PWR depends on this minimum CIF.

In this study, a technique to optimize the CIF has been developed by eliminating the excessive conservatism in ABB/CE's. A correlation is introduced to

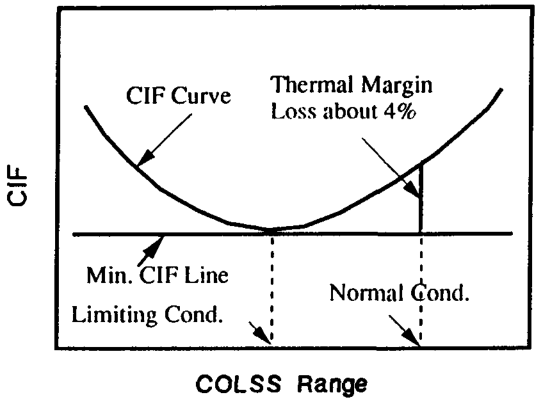

Fig. 1. Conceptional Comparison of Minimum CIF with CIF Curve

account for the actual variation of the CIF within the operating limits of the core, which results in the increase in the DNB-OPM near the normal operating condition.

2. Background

2.1. Method of DNB Evaluation

The upper bound of the nucleate boiling regime is termed the "departure from nucleate boiling"(DNB). At this point, there is a sharp reduction of the heat transfer coefficient, which would result in higher cladding temperatures and the possibility of cladding failure.

The margin to DNB in the core is expressed in terms of the DNBR(DNB ratio). The DNBR of a heated flow subchannel is defined as the ratio of the critical heat flux(CHF) required to produce DNB at the calculated local coolant conditions to the actual local heat flux.

$$DNBR = \frac{Q''_{CHF}}{Q''_{LOCAL}} \quad (2)$$

where Q''_{CHF} is a predicted CHF and Q''_{LOCAL} is an actual local heat flux.

The local flow rate and enthalpy, used for evaluating a rod bundle DNB, should be obtained from subchannel analysis. The rod bundle is considered to be an array of subchannels. The subchannels are axially segmented into a series of control volumes. Flow conditions of the control volume are calculated by simultaneous solution of the mass, energy, and momentum equations.

The CE-1 CHF correlation of ABB/CE was developed in conjunction with the TORC code, a coolant centered subchannel analysis code, specifically for DNB-OPM predictions for fuel assemblies[6, 7]. The CE-1 correlation is used with the TORC and the CETOP-D codes to determine MDNBR values for normal operation and AOOs.

2.2. CETOP-D Inlet Flow Factor(CIF)

The CHF is a function of the coolant properties and the flow subchannel geometry. The CE-1 correlation has six variables : four state variables and two geometry variables[6, 7].

$$Q''_{CHF}(\text{CE-1}) = f(P.\ G_L,\ h_{fg},\ x,\ D,\ D_M), \qquad (3)$$

where P : system pressure,
G_L : local mass flux at CHF location,
h_{fg} : latent heat of vaporization,
x : local quality at CHF location,
D : heated equivalent dia. of the subchannel,
D_M : heated equivalent dia. of a matrix subchannel.

The system pressure, latent heat, local heat flux and subchannel geometries(D, D_M) of the CETOP-D and the TORC models are the same. But the local mass flux and local quality depend on the numerical scheme of the analysis code and the flow channel layout for representing the core. They produce the MDNBR deviation of the CETOP-D from the TORC. To adjust this MDNBR deviation, the CETOP-D model uses a CIF as an adjustment factor to make the local mass flux the same as or conservative than that of the TORC model. The difference in local quality is tuned automatically since the local quality is a function of local mass flux adjusted by CIF. If the operating condition change, the CIF would be changed.

The current benchmarking method of the CETOP-D model is to find the conservative CIF which covers the entire operating ranges of the core. The CIF is implemented to the CETOP-D code as an inlet boundary condition of the hot assembly. it is multiplied to the core average inlet mass flux.

2.3. Mass Flux Variation along the Hot Subchannel

The subcooled coolant from the core inlet is heated continually along the vertical subchannels by fuel rods. The typical axial mass flux profiles of the hot subchannel ,calculated by the TORC code, are shown in Figure 2 as a function of system pressure. The mass flux in the hot subchannel increases rapidly as the coolant goes upward from the core inlet to near one third of the active core height since higher cross flow from the neighboring assemblies surges into the hot assembly, which has the relatively lower inlet flow factor than those of its neighbors(Figure 3). This flow mixing due to inlet flow maldistribution diminishes from the point of near one third of the active core height as shown in Figure 2. After this point, the

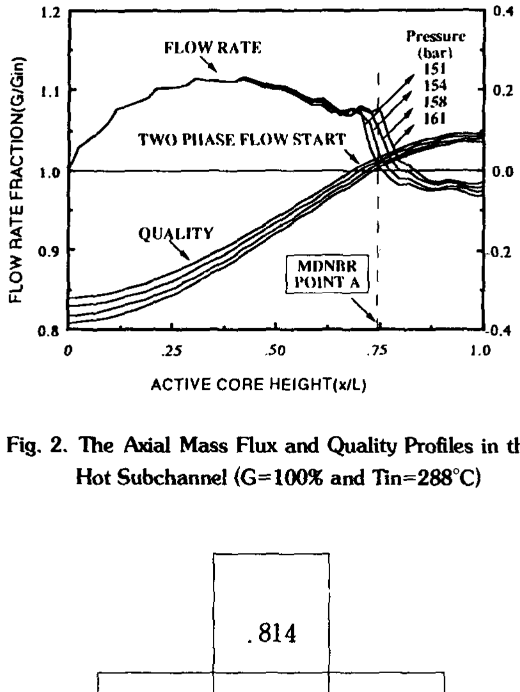

Fig. 2. The Axial Mass Flux and Quality Profiles in the Hot Subchannel (G=100% and Tin=288°C)

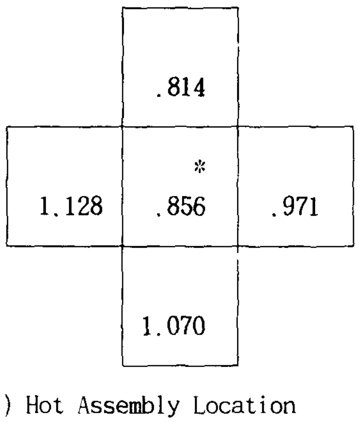

Fig. 3. Inlet Flow Factors around Hot Assembly (YGN 3&4 Flow Model Test Results)[8]

mass flux decreases smoothly till it meets saturation because of the mild volume expansion of the coolant. The beginning point of saturation could be found from the axial quality profiles in Figure 2. There is a transition region in which the mass flux decreases abruptly just after the beginning point of saturation because of the large volume expansion of the coolant[9]. The mass flux tends to be constant after this transition region.

3. Optimized Thermal Margin Model

The ABB/CE method of the DNB-OPM calculation uses the minimum CIF which is tuned at the most limiting condition of reactor operation. But the actual CIF is varying according to the state parameters which are measured at every second in COLSS. At the normal operating condition, there is some loss of DNB-OPM due to the use of the minimum CIF as shown in Figure 1.

The gain in the DNB-OPM is possible at the normal operating condition by using a CIF correlation which can account for the variation of CIF in the operating space of the core. The variables of the correlation are limited by the axial shape, system pressure, inlet temperature, and core average inlet mass flux that can be obtained by the on-line monitoring system of the reactor. Three major state parameters (system pressure, inlet temperature, and average inlet mass flux) are considered as the predictor variables of the CIF correlation. Those parameters can be obtained by the on-line monitoring system of the reactor for the following ranges[5](YongGwang Units 3&4 Cycle 1).

P: 141～164 bar,
T: 288～300°C,
G: 70～120% of thermal design flow rate.

To make the CIF correlation as a function of the operating condition of the core, 160 operating conditions were selected by the combination of three parameters listed below.

P(bar) : 141, 144, 148, 151, 154, 158, 161, 164 [8 points]
T(°C) : 288. 0, 290. 5, 293. 3, 295. 8, 300. 0 [5 points]
G(%) : 70, 85, 100, 120 [4 points]

Combination total 8*5*4 = 160 cases

Based on the sensitivity study[5], the chopped cosine axial power shape was used as a limiting shape.

Each of the best estimated CIFs was calculated according to the following procedure :

1) Generate TORC and CETOP-D input for the same assembly location.
2) Find the heat flux near the DNB SAFDL using the power iteration scheme of CETOP-D.
3) Calculate MDNBRs of TORC and CETOP-D at the same heat flux of step 2).
4) Determine the best estimated CIF through the CIF iteration. The CIF iteration stops when it satisfies the CETOP-D benchmarking criterion.

Figures 4 and 5 represent the variations of the local mass flux calculated by TORC and the best estimated CIF for the 160 operating conditions, respectively.

3.1. The Variation of the Local Mass Flux

The axial mass flux profile of the hot subchannel depends on the state parameters. Those parameters change the inception of two-phase flow that determines the local mass flux at the MDNBR location. Three flow conditions can be singled out at the MDNBR point A in Figure 2. They are single-phase, two-phase low quality and two-phase high quality regions.

a) Single-phase region

In the single-phase region, the local mass flux at the MDNBR location is relatively high and insensitive to pressure and inlet temperature. This region is dominant at a high average inlet mass flux condition (G = 120% in Figure 4).

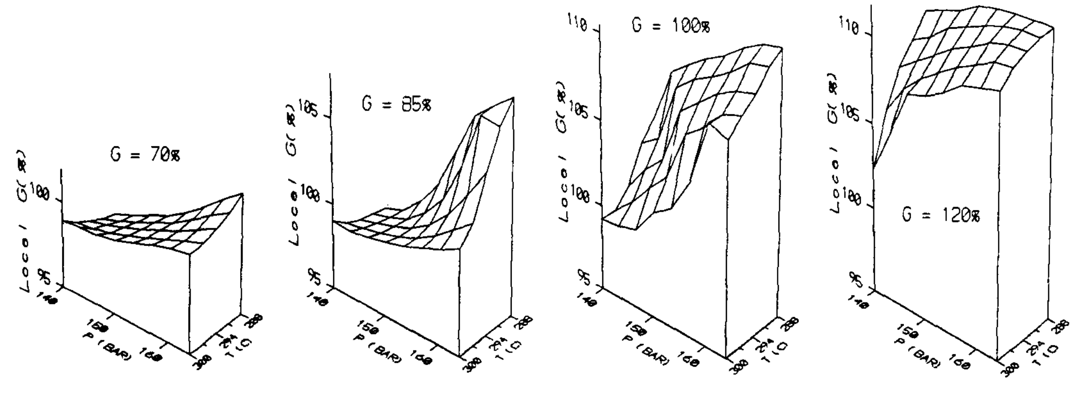

Fig. 4. The TORC Local Mass Flux Variation at the MDNBR Location

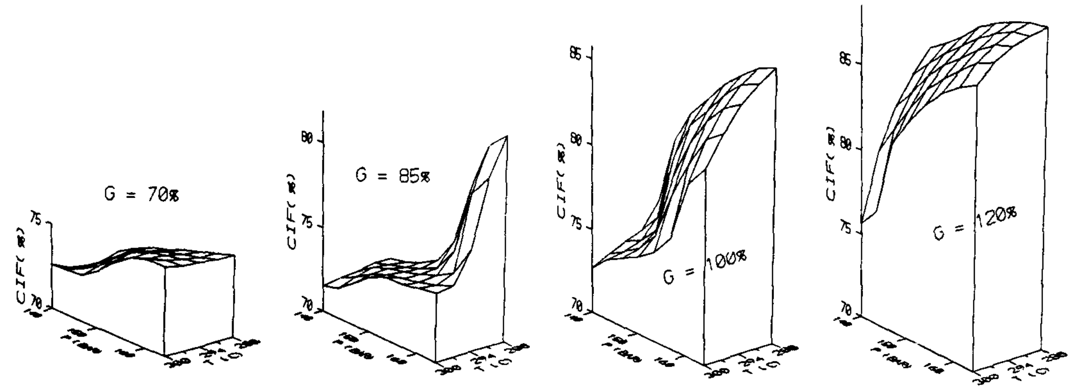

Fig. 5. The Best Estimated CIF Variation

b) Two-phase low quality region

In this region, the local mass flux at the MDNBR location is sensitive to pressure and inlet temperature. The point A in Figure 2 shows that the normalized local mass flux is abruptly reduced by volume expansion of the coolant near the MDNBR point. The inception of two-phase flow is a function of pressure, therefore the drop point of local mass flux is shifted to the top of the fuel rod as the pressure increases. It means that the stiff change of local mass flux takes place at the MDNBR point by pressure. The similar trend can be found for the temperature variation also(G = 100% and 85% in Figure 4).

c) Two-phase high quality region

The local mass flux at the MDNBR location is relatively low and insensitive to the operating parameters. This region is dominant at a lower average inlet mass flux condition(G = 70% in Figure 4) and has flat mass flux variation for pressure and inlet temperature.

As shown in Figure 4, the local mass flux generally has a clear trend for the state parameters in all the regions. As shown in Figure 5, the CIF increases as the average inlet mass flux and system pressure increase, but decreases as the inlet temperature increases.

3.2. Optimized CIF Correlation

Figure 5 represents the variation of the best estimated CIF for the various operating conditions. The trend of the variation of CIF is similar to that of the local mass flux predicted by TORC explained in Section 3. 1 as expected. The following CIF correlation form was determined by the graphic analysis of 160 data.

$$CIF_P = B_0 + B_1 \tanh(B_2 + B_3 TP + B_4 G^{0.1}\sqrt{P}) + B_5(G-1)^3 \quad (4)$$

where CIF_P : predicted CIF,

T : T/T_{REF}, $T_{REF} = 564.5$,

P : P/P_{REF}, $P_{REF} = 2250$,

G : G/G_{REF}, $G_{REF} = 2.629*10^6$,

B_N : correlation coefficients.

The correlation coefficients were obtained from 160 data points in the operating range of the core using the non-linear least squares method[10], and the results are as follows :

B0 = 0.7972, B1 = 0.0810,
B2 = −47.314, B3 = −25.292,
B4 = 72.752, B5 = −0.2258,

For some cases, this correlation produced the CIFs smaller than the best estimated CIFs as represented in Figure 6. For these cases, the CETOP-D model violated the benchmarking criterion of the equation (1). As shown in Figure 7, an optimization of the CIF correlation has been done by shifting the mean of the predicted CIF to meet the benchmarking criterion. The quantity of adjustment can be expressed in terms of the bias of the mean.

$$\text{Bias} = \text{Max}(R) = .03, \quad (5)$$

where $R = CIF_P - CIF_{BE}$

The optimized CIF correlation is as follows :

$$CIF_O = CIF_P - \text{Bias} \quad (6)$$

$$= (B_0 - Bias) + B_1 \tanh[B_2 + B_3 TP + B_4 G^{0.1}\sqrt{P}] + B_5(G-1)^3$$

where CIF_O is the optimized CIF. This optimized CIF correlation has the mean and the standard deviation of the ratio of the predicted to the best estimated CIF of 0.97 and 0.012 for the 160 source data, respectively.

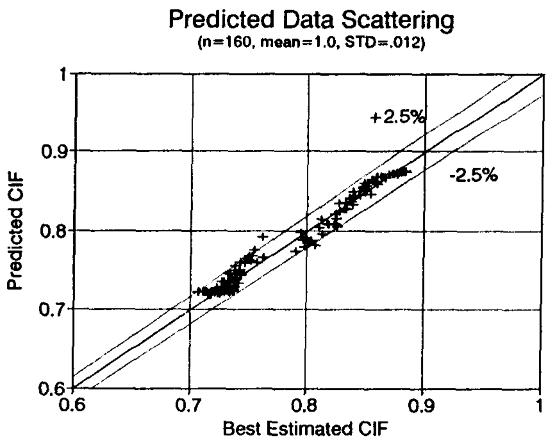

Fig. 6. Comparison of Predicted CIF with Best Estimated CIF

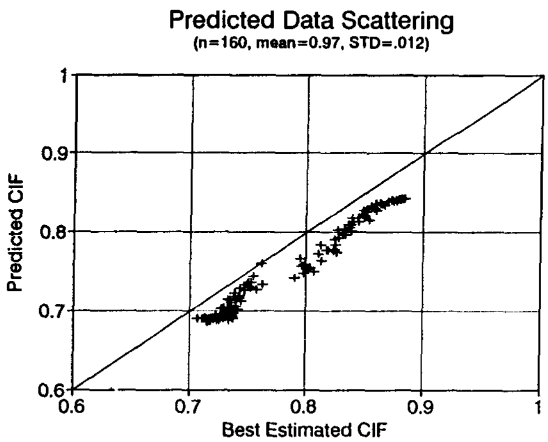

Fig. 7. Optimized(Tuned) CIF Distribution

3.3. DNB Overpower Margin Assessment

The DNB-OPM is defined as follows:

DNB-OPM = AOPM - ROPM - (PMS Uncertainty),

where

AOPM (Available overpower margin):
thermal power at the DNB SAFDL,

ROPM(Required overpower margin):
safety margin to cover the AOOs,

PMS(Plant monitoring system) Uncertainty:
power margin including all the PMS uncertainties.

To estimate the amount of DNB-OPM gain by the optimized CIF correlation, the ROPM and PMS uncertainty were set equal. The DNB-AOPM of the YonGwang Units 3&4 Cycle 1 was calculated at the normal operating condition by using both ABB/CE and present methods, respectively. The DNB-AOPM and the corresponding CIF are listed in Table 2 with the results obtained by the TORC code.

As shown in Table 2, the DNB-OPM is increased by 2% at the normal operating condition which is the half of the DNB-OPM lost of 4%.

4. Conclusions

A technique to optimize the CETOP-D inlet flow factor has been developed by eliminating the excessive conservatism in the ABB/CE's. A correlation for the CETOP-D inlet flow factor has been introduced to account for the variation of the inlet flow factor in the operating space of the reactor core. Through the parametric study, it turned out that the CETOP-D inlet flow factor has a clear trend for the state parameters; The CIF increases as the average inlet mass flux and the system pressure increase, but decreases as the inlet temperature increases. From this trend, a successful CIF correlation has been developed, which has a standard deviation of 0.012.

This new method was applied to the core operating range of the YongGwang Units 3&4 Cycle 1. The DNB overpower margin was increased by 2% compared with the result of the ABB/CE method at the normal operating condition. Usually the reactor operating margin of the ABB/CE type reactor is 4−6% at the normal operating condition. Therefore, it can be concluded that the present method contributes to give a surfficient core operating margin or give a chance to uprate the nuclear power plant.

Table 2. Estimation of DNB Overpower Margin Gain (Initial Core Design of YGN 3, 4)

Method	MDNBR	CIF	DNB-AOPM (%)	DNB-OPM Gain (%)
Exact(TORC)	1.506	.82	149	4
Present(CETOP)	1.472	.77	147	2
ABB/CE(CETOP)	1.437	.72	145	ref.(0)

Power: 100%
Nominal condition: T = 295.8°C,
P = 158 bar,
G = 100% of thermal design flow rate

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