Thermal Margin Budget of a Simplified Core Thermal-Hydraulic Code for OPR1000

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1. Introduction

A thermal-hydraulic analysis of a pressurized water reactor (PWR) core is usually conducted by a subchannel analysis method to prove a safe and reliable operation of a reactor. The reactor core is divided into a number of subchannels within which the thermal-hydraulic conditions are considered to be radially uniform. The coolant moves through the subchannels formed between neighboring fuel rods and between the peripheral fuel rods and the reactor core shroud. A subchannel code such as THINC-IV [1] and TORC [2] solves the mass, momentum and energy equations for the subchannels by the finite-difference method. They calculate the minimum departure from nucleate boiling ratio (DNBR) in a PWR core which is a measure for the core thermal margin.

A simplified thermal-hydraulic code, CETOP-D [3], was developed to quickly calculate the minimum DNBR (MDNBR) based on a four-channel core model. A three-dimensional transport coefficient model is used to radially group a flow subchannel into a 4-channel core representation. The CETOP-D model also includes an adjusted hot assembly inlet flow factor to account for the deviations in the MDNBR due to a code simplification. The hot assembly flow factor is adjusted to eliminate a possible non-conservatism in the MDNBR prediction by the CETOP-D code. The CETOP-D code and its simplified versions are used to calculate the MDNBR for on-line core monitoring and protection systems as well as a safety analysis for a Korea optimized PWR, OPR1000.

The purpose of this study is to estimate the conservatism in CETOP-D MDNBR and the potential DNBR margin enhancement for the CETOP-D applications. The MDNBR values by the TORC and CETOP-D codes were compared for a wide range of operating conditions for the OPR1000.

2. Code and Model Description

2.1 Core Thermal-Hydraulic Code Description

The TORC code determines the coolant conditions in a reactor core for a steady-state operation. TORC uses an iterative solution technique to solve the conservation equations for a three-dimensional representation of an open-channel reactor core. Lateral transfer of mass, momentum and energy between flow channels is accounted for in the calculation of the local coolant conditions. These coolant conditions are used with a critical heat flux correlation to determine the MDNBR for a core.

The CETOP-D code solves the transport coefficient conservation equations by the finite-difference method. The conservation equations in the finite-difference form are solved by a non-iterative numerical scheme, i.e., a prediction-correction scheme. The prediction-correction method is a non-iterative numerical scheme which provides a fast solution for thermal-hydraulic parameters at each axial elevation from a core inlet to outlet.

2.2 Core Models for TORC and CETOP-D

The TORC code uses a multi-stage model to perform core-wide and limiting fuel assembly analyses. The core-wide analysis determines the coolant conditions throughout a core quadrant containing a limiting fuel assembly. The smallest unit of a flow channel in the core-wide analysis is typically a single fuel assembly. The limiting fuel assembly analysis determines the local coolant conditions in the limiting subchannel for the assembly quadrant containing the limiting subchannel. The MDNBR is determined for the most limiting subchannel in a reactor core.

The CETOP-D code calculates the MDNBR in a hot assembly of a core. A one-fourth (1/4) of the hot assembly and the remainder of a core are modeled as two individual lumped subchannels, i.e., channels 1 and 2. The hot assembly is modeled by three lumped channels, i.e., channels 2, 3 and 4. The hot subchannel is channel 4. Channel 2 is a quadrant of the hottest assembly in a core and Channel 1 is an assembly representing the average coolant conditions for the remaining portion of a core. Lumped channel 2 includes channels 3 and 4. Channel 3 lumps the subchannels adjacent to the MDNBR hot channel 4. The radial rod peaking factors and the inlet mass flux of the hot assembly are selected from a detailed subchannel analysis such that under these two conditions the MDNBR will be calculated conservatively as compared to a detailed assembly-by-assembly analysis.

3. Thermal Margin Assessment

The MDNBR values by the TORC and CETOP-D codes were calculated for a wide range of operating conditions for the OPR1000 reactor listed in Table I. The hot assembly inlet flow factor for the CETOP-D code was determined such that the CETOP-D MDNBR is lower than the TORC MDNBR at a limiting condition.

Table I: Wide Range of Reactor Core Operating Conditions for OPR1000

Core state parameter	***Value***
Inlet temperature, Tc (^oC)	260 - 313
Pressure, Pr (bar)	125 - 170
Mass flux, G (% rated)	80 - 125
Axial shape index, ASI	-0.6 - +0.6

Fig. 1 shows the CETOP-D MDNBR with respect to the TORC MDNBR for 96 operating conditions. It can be seen that the CETOP-D MDNBR is lower than the TORC MDNBR at any of the wide operating conditions. The difference between the CETOP-D and TORC MDNBR values (ΔMDNBR) is calculated as -1.5%(minimum) and -14.6%(maximum) depending on the operating conditions. The mean value and standard deviation of the ΔMDNBR are estimated as 10.0% and 2.6%, respectively.

Fig. 2 illustrates the MDNBR difference between CETOP-D and TORC depending on the axial shape index (ASI) of the core power distribution. The CETOP-D MDNBR appears to be smaller than the TORC MDNBR by more than 10% for the negative ASI. Particularly in the narrow range of the normal operation, e.g., -0.1 < ASI < 0.1, the conservatism of the CETOP-D MDNBR is in the range of 8% and 15%.

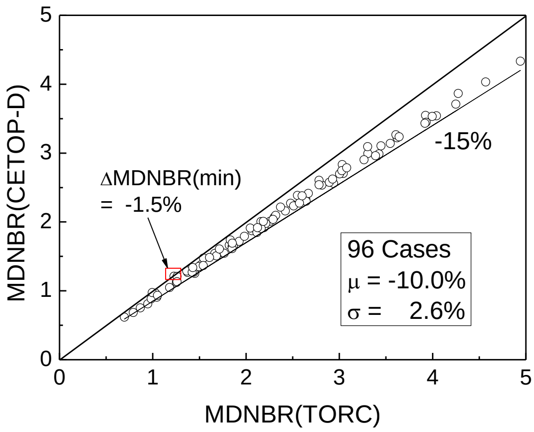

Fig. 1. Comparison of the CETOP-D and TORC MDNBR.

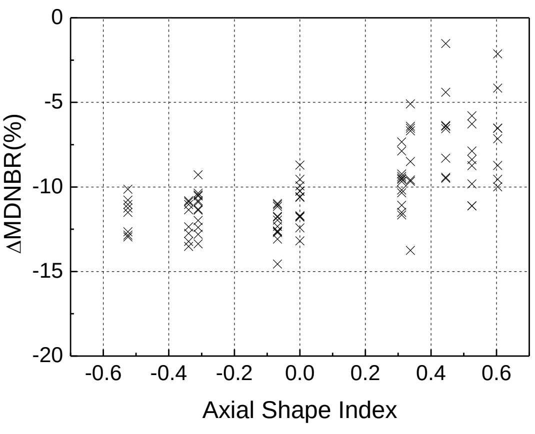

Fig. 2. MDNBR difference depending on axial shape index.

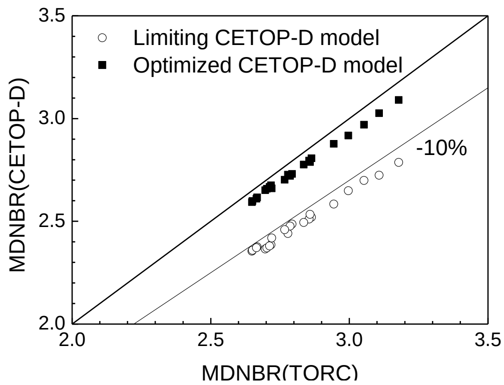

Fig. 3. CETOP-D MDNBR conservatism near a nominal operating condition.

The hot assembly flow adjustment factor for the CETOP-D code was found to give an excessive conservatism in the CETOP-D MDNBR during the normal reactor operation near a nominal condition (i.e., 100% power, G=105% rated, Pr=158 bar, Tc=295 ^oC, -0.1<ASI<0.1). For the core conditions in the normal operating range by accounting for the measurement uncertainties of the core state parameters, the CETOP-D MDNBR is compared with the TORC MDNBR in Fig. 3. It shows that the CETOP-D MDNBR with a liming model is lower than the TORC MDNBR by more than 10% for the reactor operation near a nominal core condition. The optimized CETOP-D model with a best estimate hot assembly flow factor is shown to increase the DNBR margin by reducing the excessive conservatism of the limiting model.

4. Conclusions

A simplified core thermal-hydraulic code, CETOP-D, was compared against the best-estimate subchannel code, TORC. The minimum DNBR values by CETOP-D and TORC were calculated for a wide range of the OPR1000 core operating conditions. The hot assembly inlet flow factor for the CETOP-D assures the conservatism of the CETOP-D MDNBR but also results in a loss of the DNBR margin more than 10% during normal reactor operation near a nominal condition. Hence, a significant amount of the DNBR margin can be recovered in the OPR1000 by using different values of the CETOP-D hot assembly flow factor which is adjusted for a reactor operation inside and outside a prescribed operating range.

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