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A Validation of Subchannel Based CHF Prediction Model for Rod Bundles

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1. Introduction

An accurate prediction of the critical heat flux (CHF) in rod bundles is essential for core thermal hydraulic design of water-cooled nuclear reactors. Owing to the complexity of channel geometry and incomplete understanding of CHF phenomena in rod bundles, a number of empirical CHF correlations accompanied with relevant CHF data base have been developed for design applications. The limitations on the CHF test facility render a use of local parameter CHF prediction model by employing a subchannel analysis code.

Various studies have been conducted at KAERI to identify the CHF characteristics as well as to improve the CHF prediction models in rod bundles under advanced PWR core conditions. In this context, extensive assessments of rod bundle CHF data base have been performed for PWR and APWR conditions [1]. A large number of CHF data base were procured from various sources which included square and non-square lattice test bundles. CHF prediction accuracy was evaluated for various models including CHF lookup table method, empirical correlations, and phenomenological DNB models. The parametric effect of the mass velocity and unheated wall has been investigated from the experimental result, and incorporated into the development of local parameter CHF correlation applicable to APWR conditions.

According to the CHF design criterion, the CHF should not occur at the hottest rod in the reactor core during normal operation and anticipated operational occurrences with at least a 95% probability at a 95% confidence level. This is accomplished by assuring that the minimum DNBR (Departure from Nucleate Boiling Ratio) in the reactor core is greater than the limit DNBR which accounts for the accuracy of CHF prediction model. The limit DNBR can be determined from the inverse of the lower tolerance limit of M/P that is evaluated from the measured-to-predicted CHF ratios for the relevant CHF data base.

It is important to evaluate an adequacy of the CHF prediction model for application to the actual reactor core conditions. Validation of CHF prediction model provides the degree of accuracy inferred from the comparison of solution and data. To achieve a required accuracy for the CHF prediction model, it may be necessary to calibrate the model parameters by employing the validation results. If the accuracy of the model is acceptable, then it is applied to the real complex system with the inferred accuracy of the model. Referring to a well-established V&V concept in computational fluid dynamics [2], a relationship between prediction, calibration, and validation of CHF prediction model is established as shown in Fig. 1.

In a conventional approach, the accuracy of CHF prediction model was evaluated from the M/P statistics for relevant CHF data base, which was evaluated by comparing the nominal values of the predicted and measured CHFs. The experimental uncertainty for the CHF data was not considered in this approach to determine the limit DNBR. When a subchannel based CHF prediction model is concerned, however, the experimental uncertainty should be reflected in evaluating the subchannel thermal hydraulic parameters which are not measured during CHF experiments. In the traditional design of PWR cores, the influence of CHF experiment uncertainty is not explicitly considered in the limit DNBR. It may be acceptable when the uncertainty of an empirical CHF correlation is considerably larger than the experimental uncertainty. However, it should be noted that the influence of experimental uncertainty may depend on various factors such as the accuracy of CHF model, quality of the test facility, uncertainty of subchannel analysis code, and the number of available CHF data.

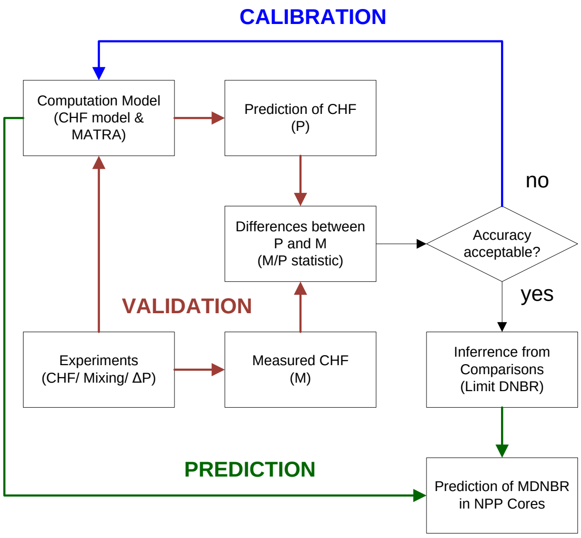

Fig. 1. Relationship between validation, calibration, and prediction of CHF in rod bundles

In this study, a validation of subchannel based CHF prediction model was conducted according to the validation procedure suggested by ASME [3]. The AECL-IPPE 1995 CHF lookup table method [4] in connection with a subchannel analysis code MATRA [5], and Rod bundle CHF data base simulating SMART fuel assembly were involved in the validation. Validation uncertainty of the CHF prediction model was evaluated for a selected CHF data, and its influence on the limit DNBR was investigated.

2. Methods and Results

2.1 Validation Procedure

Validation of CHF prediction model was conducted according to the procedure shown in Fig. 2. Experimental CHF data for SMART test bundles were examined by the AECL-IPPE 1995 CHF lookup table method. Subchannel local conditions for the CHF prediction model were calculated by the MATRA code. The uncertainty parameters for the predicted DNBR were composed of two parts: experimental parameters for MATRA input variables and parameters of MATRA code models. The validation uncertainty of the CHF prediction model was estimated according to the validation procedure suggested by ASME. It quantifies the uncertainty of comparison error for a specified variable, i.e. DNBR, at a specified validation point. The limit DNBR is inferred from the comparison errors evaluated for all data points. For estimating the validation uncertainties of individual data point, a sensitivity coefficient approach (or, Taylor series approach) was applied to evaluate a propagation of experimental uncertainties to the predicted CHF. The limit DNBR was calculated by considering the validation uncertainty for individual CHF data.

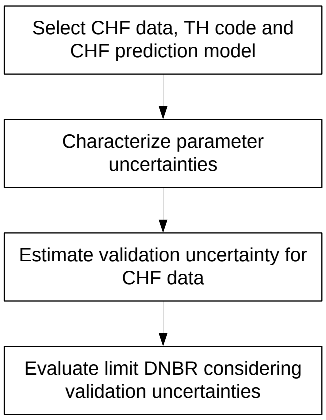

Fig. 2. Validation procedure for CHF prediction model

2.2 CHF Experiment and CHF Prediction Model

The CHF experiment for SMART fuel simulators has been conducted in a high-pressure water test loop at Stern Laboratories in Canada. The major components of the test loop consist of test section, gas pressurizer, mixers, heat exchangers, condenser, main coolant pump, and preheater. The test section includes the pressure housing, flow channel, fuel simulators, spacer grids, and instrumentation. The test bundle consists of twenty-five indirectly heated rods with a 9.5 mm outer diameter. The test section and test loop were instrumented to measure the power, flow rate, absolute/differential pressures, and coolant temperature during testing. The uncertainties of the heater rods/flow channel dimensions and the test conditions were originated from the fabrication tolerance and instrumentation errors.

The AECL-IPPE 1995 CHF lookup table was selected as the local parameter CHF prediction model. The local thermal hydraulic conditions were calculated by the subchannel analysis code, MATRA. To compare with the experimental data, the CHF was determined at the predicted minimum DNBR location with a heat balance method (HBM). In addition to the existing correction factors for rod bundles, a complementary correction factor for rod bundles was developed from an extensive assessment of rod bundle CHF data for PWR and advanced PWR conditions [6]. Tong's F-factor was applied for axially non-uniform power shapes. The accuracy of the CHF table method with modified correction factors was examined for the SMART bundle CHF data. The mean and standard deviation of M/P were calculated by 1.011 and 0.090, respectively. According to a traditional approach, the limit DNBR for a normally distributed M/P data can be evaluated by

$$DNBR_{Limit} = \frac{1}{\left(M/P\right)_{mean} - k_{95/95} \cdot s} \tag{1}$$

where '$(M/P)_{mean}$' is the mean value of M/P, 's' is the sample standard deviation of M/P, and $k_{95/95}$ is the one-sided tolerance limit factor. For the selected CHF data, the limit DNBR of the modified CHF lookup table was evaluated as 1.174.

2.3 Estimation of Validation Uncertainty

The uncertainty of the CHF prediction model was estimated against selected steady-state CHF data according to the standard of the V&V procedure issued by ASME. The final goal of this standard is to evaluate the uncertainty range of the model error from the validation comparison error and the validation uncertainty. If we neglect the code solution uncertainty (u_{num}), the validation uncertainty can be estimated by

$$u_{val} = \sqrt{u_{input}^2 + u_M^2} \tag{2}$$

where the standard uncertainties u_{input} and u_M are the estimates of errors for the input parameters and measured data, respectively.

The procedure of uncertainty analysis by the sensitivity coefficient approach is shown in Fig. 3. According to the sensitivity coefficient approach, the input uncertainty is calculated by combining the sensitivity coefficients and the coefficient of variations for each input parameter. That is, for statistically independent parameters,

$$u_{input} = \sqrt{\sum_{k}^{all} \left(S_k \frac{\sigma_k}{\mu_k} \right)^2} \tag{3}$$

The sensitivity coefficient (S_i) is defined as the ratio between the percent change of DNBR to the percent change of input parameter. It is evaluated by changing the parameter in 3σ from its nominal value.

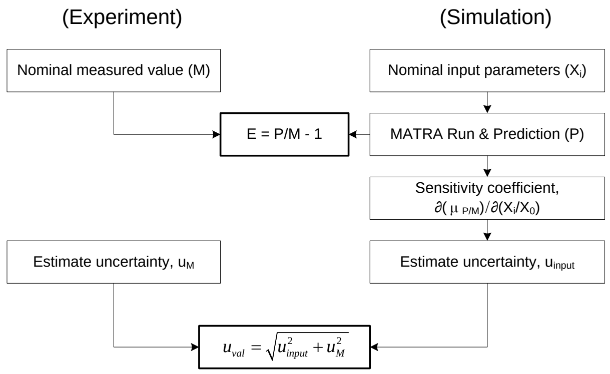

Fig. 3. Uncertainty analysis by sensitivity coefficient approach

Twelve parameters are selected for the uncertainty analysis as described in Table I. The sensitivity coefficient for each parameter was calculated at the minimum DNBR location for a steady-state rod bundle CHF data with non-uniform axial power shape: pressure of 15.57 MPa, inlet temperature of 280.2 deg-C, inlet mass flux of 1002.3 kg/m^{2}s, and bundle heat flux of 1058.2 kW/m^2. The estimated values the coefficient of variation, sensitivity factor, and importance factor (I.F.) for each parameter are listed in Table I. The uncertainties of the inlet temperature and the bundle heat flux were estimated as fixed values of 0.4 ^{o}C and 7.2 kW/m^2, respectively. The uncertainty parameters for the MATRA code model were selected which may have significant influence on the distribution of local thermal hydraulic conditions in the subchannels. The uncertainties of the model parameters were evaluated on the basis of relevant experimental data for rod bundles.

Table I. Sensitivity coefficient and importance factor of uncertainty parameters

Parameter	σ /μ	S_i	*I.F.*(%)
Experiment parameters:			
Pressure	0.003	−0.477	2.1
Inlet temperature, ^{o}C	0.0014	−1.829	6.4
Inlet mass flux	0.0095	+0.467	18.5
Bundle heat flux	0.0068	−1.078	50.7
Rod diameter	0.0032	−0.065	0.04
TS channel width	0.0005	+0.608	0.07
TH code models:			
Bundle friction factor	0.1	+0.001	0.02
Grid loss factor	0.018	+0.034	0.35
TDC	0.08	+0.052	16.5
Subcooled void model	0.1	+0.003	0.08
Bulk void model	0.1	+0.024	5.22
2-ϕ friction multiplier	0.103	−0.001	0.02

According to the importance factor, which represents the contribution of a parameter to the overall uncertainty, major contributions to the overall uncertainty of DNBR were due to the heat flux, turbulent mixing parameter, inlet temperature, bulk void model, and inlet mass flux. For the selected CHF data provided in Table I, the input uncertainty was estimated as 1.03% from eq. (2). By combining the input uncertainty with the measurement uncertainty of CHF, the validation uncertainty of the CHF prediction model against this selected CHF data was estimated as 1.24% by the sensitivity coefficient approach.

2.4 Evaluation of the Limit DNBR

The validation uncertainties for all of selected CHF data were estimated using the sensitivity coefficient approach. By assuming that the sensitivity coefficients are independent on the operating conditions, the distribution of validation uncertainty was obtained as shown in Fig. 4 due to the change of the coefficient of variations at various test conditions.

The limit DNBR can be determined from the tolerance limit of M/P for the selected data base. If each M/P is a normally distributed random variable, a set of randomly selected M/P data can be employed to produce a tolerance limit of M/P ($= D_i$). For a number of random selections, a distribution of the M/P tolerance limit can be obtained as shown in Fig. 5 (red line). From this distribution, the limit DNBR was evaluated by

$$DNBR_{\text{limit}} = \mu\left(D_i\right) + k_{95/95} \cdot s\left(D_i\right) \qquad (4)$$

The mean and standard deviation of the M/P tolerance limits were calculated by 1.176 and 0.0016, respectively. From this data, the limit DNBR considering the uncertainties of CHF experiment and TH code models was evaluated as 1.179.

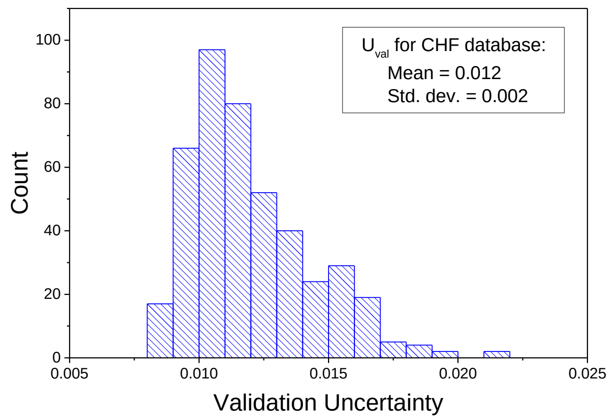

Fig. 4. Distribution of validation uncertainty for selected CHF data base

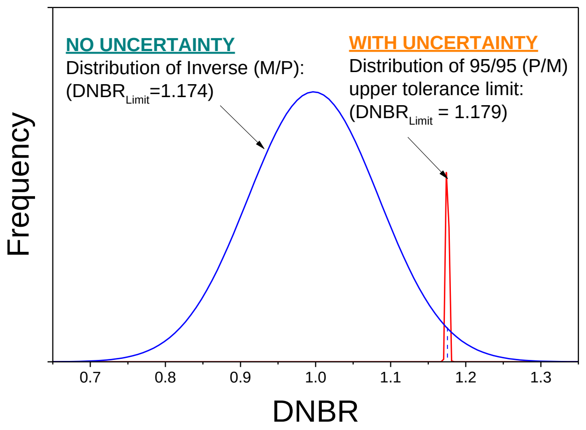

Fig. 5. Influence of experimental uncertainty on the limit DNBR

3. Conclusions

A validation procedure for a subchannel based CHF prediction model was examined by employing a CHF lookup table method and rod bundle CHF data simulating SMART fuel bundles. Propagation of the experimental uncertainty to the predicted CHF was evaluated by the sensitivity coefficient approach. For the selected 437 CHF data points obtained from a well-qualified test facility, the mean value of the validation uncertainty was calculated by 1.2%, and resulted in an increase of the limit DNBR about 0.4%. The influence on the limit DNBR would be more remarkable, however, in cases of relatively large experimental uncertainty, insufficient number of CHF data base for evaluating the limit DNBR, and more accurate/precise CHF prediction model.

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