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Prediction of Critical Heat Flux in Fuel Assemblies Using a CHF Table Method

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Abstract

A CHF table method has been assessed in this study for rod bundle CHF predictions. At the conceptual design stage for a new reactor, a general critical heat flux (CHF) prediction method with a wide applicable range and reasonable accuracy is essential to the thermal-hydraulic design and safety analysis. In many aspects, a CHF table method (i.e., the use of a round tube CHF table with appropriate bundle correction factors) can be a promising way to fulfill this need. So the assessment of the CHF table method has been performed with the bundle CHF data relevant to pressurized water reactors (PWRs). For comparison purposes, W-3R and EPRI-1 were also applied to the same data base. Data analysis has been conducted with the subchannel code COBRA-IV-I. The CHF table method shows the best predictions based on the direct substitution method. Improvements of the bundle correction factors, especially for the spacer grid and cold wall effects, are desirable for better predictions. Though the present assessment is somewhat limited in both fuel geometries and operating conditions, the CHF table method clearly shows potential to be a general CHF predictor.

1. INTRODUCTION

At the conceptual design stage of a new reactor, there are usually lacks of suitable CHF correlations or sufficient data bases. Therefore, a general CHF prediction method with a wide applicable range and reasonable accuracy is essential to thermal-hydraulic design and safety analysis. Since there are many CHF prediction methods for round tubes, some of them covering a very wide range of parameters, there have been some efforts to apply them to rod bundles. Most of these approaches, however, adopted the lumped parameter concept in connection with safety analysis codes such as RELAP5/MOD3, CATHARE, and CATHENA. With respect to the safety analysis of reactors, the lumped parameter approach may be acceptable since it can provide an approximate CHF value indicating the change of heat transfer modes. As far as the thermal margin is concerned, however, a subchannel-wise analysis is required to obtain reliable analysis results.

Recently an international CHF table was jointly developed by the AECL and IPPE based on a huge number of round tube CHF data (Groeneveld, 1996). It is generally accepted as a well-established tool of CHF prediction for tube geometry. The CHF table, along with appropriate correction factors for bundle geometric effects, may be a promising approach to fulfill the need of a generalized CHF prediction model in the following aspects: wide applicable range, extensive experience, easy update in case of the additional data, and correct asymptotic trends. The CHF look-up table method has been incorporated in several thermal-hydraulic system analysis codes to predict the bundle CHF and to indicate the heat transfer mode change from nucleate to transition boiling. The applicability of this CHF look-up table method has been widely estimated with system codes, for example, through the bundle CHF data (Lee, 1994), boil-off experimental data (Faluomi, 1997), and system transient analysis. The look-up table method is also embodied in the subchannel code of ASSERT to predict the CHF for CANDU or research reactors (Carver, 1995).

The purpose of this study is to assess the prediction capacity of the CHF look-up table method in conjunction with a subchannel code as a preliminary CHF predictor for rod bundles

2. ASSESSMENT METHOD AND DATA BASE

2.1 CHF Data

The bundle CHF data used in this analysis cover operating ranges of the conventional pressurized water reactors (PWR). A total of 1,958 CHF data points from 23 rod bundles are used in the assessments. The CHF data are simulating the conventional PWR of Westinghouse (W) (Fighetti & Reddy, 1982) and Siemens (SPC). The seven Westinghouse bundles are 5x5-rod arrays with mixing vanes that represent a W 17x17 fuel assembly. Three of these bundles are 96-inch long and the others are 168-inch long. Two of them have a guide tube at the center of the bundle and two of them have non-uniform axial heat flux distributions. The sixteen SPC bundles have also 5x5-rod array representing various vendor's fuel assemblies. Four of them have no guide tubes and the remaining twelve bundles have one guide tube. Four of them have non-uniform axial heat flux distributions. All rod bundles have spacer grids with mixing devices to enhance the CHF performance. The overall parametric ranges of the CHF data are summarized in Table 1.The subchannel code of COBRA-IV-I is employed in the analysis of CHF data.

Table 1. Parameter Ranges of Bundle CHF Data

	W	SPC	Total
No. of Bundles	7	16	23
No. of Data	480	1478	1958
Pressure (bar)	103.1-167.9	122.4-167.2	103.1-167.9
Mass flux (Kg/m^2s)	1335-6117	1281-4914	1335-4914
Quality (-)	-0.10-0.323	-0.129-0.344	-0.129-0.344
Hydraulic Dia (mm)	9.4-11.8	9.7-13.5	9.4-13.5
Heated Dia (mm)	11.8-13.6	11.6-15.6	11.6-15.6
Heated Length (m)	2.44-4.27	2.0-4.27	2.0-4.27
Grid Spacing (m)	0.56-0.66	0.23-0.63	0.23-0.66

2.2 Data Evaluation Approaches

The critical heat flux ratio (CHFR) is evaluated at the subchannel with the first CHF indication. The definition of the CHFR is as follows:

$$CHFR = \frac{\text{The predicted CHF}}{\text{The measured local heat flux}} = \frac{P}{M}$$

The measured local heat flux is determined at the axial location giving the minimum CHF ratio. But there are two different approaches in predicting CHF (Inasaka & Nariai, 1996): (a) the constant local quality approach or the direct substitution method (DSM) and (b) the constant inlet condition approach or the heat balance method (HBM). In the case of the HBM, a simple procedure is adopted (Hwang et al., 1997): a) the local mass flux distribution at a certain power level remains unchanged at different power levels and b) the enthalpy rise in a subchannel is proportional to the bundle power.

2.3 CHF Look-Up Table Method

The 1995 CHF look-up table jointly developed by the AECL and IPPE (Groeneveld et al., 1996) is used in this assessment. The bundle CHF is calculated as follows:

$$q''_{CHF} = q''_{D=8mm} \cdot K_1 \cdots K_i$$

where $q''_{D=8mm}$ is the CHF value given by the look-up table for 8-mm diameters tubes and K_i is a correction factor accounting for a subchannel specific effect. A set of correction factors which was originally proposed by Groeneveld et al. (Groeneveld, 1986), is used in this assessment to take into account the bundle effects.

3. RESULTS AND DISCUSSIONS

3.1 Estimation of the Best Achievable Errors for Look-up Table Method

In general, the CHF phenomenon in rod bundles is more complex and obscure than that in a round tube. Thus the minimum expected error of the CHF table method for a set of rod bundle CHF data base can be assessed by analyzing a set of round tube CHF data corresponding to the parametric ranges of interest. For this purpose, 375 data points which belong to the parametric ranges of conventional PWR conditions are selected from the KAIST CHF data bank. As the best achievable errors of the CHF table method, the mean and standard deviation by DSM are calculated as 1.039 and 0.1472, respectively, while those by HBM are 1.006 and 0.0406, respectively.

3.2 Rod Bundle Data Analysis

The CHF look-up table method is assessed using the HBM as well as the DSM. In addition, for comparison purposes, W-3R (local condition type) and EPRI-1 (mixed condition type) correlations are applied as the typical tube-based bundle CHF predictor and bundle-based CHF predictor, respectively. The statistical results for the look-up table, W-3, and EPRI-1 are summarized in Table 2.

(a) Direct Substitution Method

Applying the CHF table method to the rod bundles, the deviation of the mean of P/M from the best achievable statistic reveals about 14%, while that of the standard deviation shows within 1%. This result implies the applicability of the CHF table method to rod bundles with appropriate modifications of bundle correction factors. The parametric distribution of P/M values with respect to pressure, mass flux and quality are shown in Fig. 1. It shows randomly distributed errors around the mean, and no systematic errors are detected. The W-3R correlation tends to overpredict the bundle CHF data by ~18% with a standard deviation of 33%. The main reason for the large deviation may be attributed to the narrow applicable ranges of the R-grid factor, which does not cover a lot of data with small rod diameter and pitch used in the present assessment.

(b) Heat Balance Method

For the HBM the statistical results of the CHF look-up table method are 0.951 of mean and 0.0637 of standard deviation. The differences of the mean and standard deviation from the best achievable errors are about 5% and 2.5%, respectively. This accuracy is comparable to the EPRI-1 correlation which calculates the mean and standard deviation as 0.975 and 0.0656, respectively

3.3 Evaluation of Correction Factors for Bundle Specific Effects

The influence of spacer grids, unheated wall, and non-uniform axial heat flux distributions are also evaluated on the basis of the DSM by introducing correction factors for each bundle specific effect. In order to examine each bundle effect separately, a reference case is established with standard bundles having a uniform axial heat flux and no guide tube. The performance of a correction factor is evaluated from the viewpoint of prediction accuracy and parametric trends. The results of the estimation of correction factors are summarized in Table 3.

(a) Spacer Grid

A spacer grid correction factor of K_3 is introduced to take into account, not only the effect of the grid design, but also the effect of the grid span. These effects are reflected by empirical coefficients of a and b in the correction factor. By applying this factor to standard bundles consisting of 639 data points, the mean and the standard deviation are calculated to be 0.948 and 0.1769, respectively. If the correction factor is not applied, the mean of P/M reduces by about 5%. Considering the enhancement of the CHF caused by a spacer grid with mixing devices, this amount of P/M reduction must have been underestimated. Figure 2 shows a comparison between K_3 and M/P calculated without a correction factor with respect to the ratio of grid span to hydraulic diameter, L_{sg}/D_{hy}. The values of K_3 are calculated with the local conditions at CHF locations. As a whole, the M/P decreases with L_{sg}/D_{hy}, but the trend is not monotonic due to the differences of grid design. This means that the pressure loss coefficient is not enough to represent the effects of the turbulent intensities or swirl motions created by various types of spacer grids in terms of CHF enhancement.

(b) Cold Wall

Existence of a guide tube deteriorates the heat removal capacity since the coolant flow near the cold wall bypasses without cooling the heated wall. This effect is taken into account by the K_1 factor replacing the tube diameter with the heated equivalent diameter. As shown in Table 3, the CHF table method without K_1 overpredicts the CHF data by about 10% compared with the reference case, while the table with K_1 underestimates the CHF values by about 6%. This implies that the present correction factor using a heated equivalent diameter exaggerates the effect of the unheated wall in rod bundles, and new correction factors should be introduced.

(c) Non-Uniform Axial Heat Flux

It is generally known that the CHF in a decreasing heat flux region is less than that in a uniform heat flux region at the same local conditions. This effect is evaluated by introducing Tong's F-factor and Groeneveld's K_5 factor based on the boiling length average heat flux. As shown in Table 3, it reveals that Tong's F-factor properly reflects the non-uniform heat flux effect with the CHF table method, while Groeneveld's K_5 factor tends to overemphasize the non-uniform heat flux effects. Figure 3 represents the equivalent non-uniform heat flux characteristics of two methods in case of the chopped cosine shape along with quality variation when the non-uniform effect is taken into account. Since the corrected local heat flux becomes higher than the actual heat flux after the rod peak heat flux, the CHF location is generally shifted toward the exit for both methods. It is found that if the CHF occurs before the peak heat flux the Tong F-factor method conservatively predicts the effect than boiling length average heat flux concept, but after the peak heat flux, the trend becomes opposite.

4. CONCLUSIONS

The look-up table method for bundle CHF prediction in conjunction with a subchannel code has been assessed for PWR conditions. Important findings are summarized as follows:

(a) The CHF look-up table method is better than W-3R correlation with the DSM approach, and comparable to the bundle correlation of EPRI-1 with HBM approach.
(b) The correction factors, especially related to the spacer grid and cold wall, need to be further improved to account properly for the bundle geometrical effects.
(c) According to the present assessment, the CHF table method has great potential to be a general CHF predictor for the rod bundles. In the conceptual design stage, when the CHF prediction models or CHF data bases, are not available, the CHF look-up table method may be used in CHF evaluation for the preliminary analysis.

5. REFERENCES

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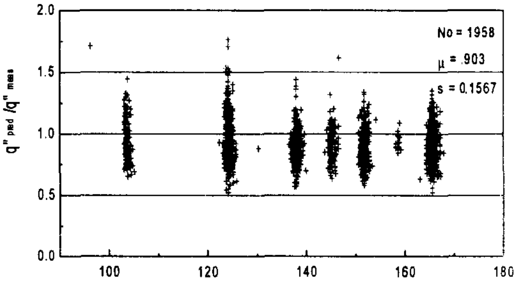
Table 2. Statistical Results of CHF Predictors for Rod Bundle Data

No. Of Data	DSM				HBM			
	Look-up Table		W-3R		Look-up Table		EPRI-1	
	Mean	Stand. Dev.	Mean	Stand. Dev.	Mean	Stand. Dev.	Mean	Stand. Dev.
1958	0.903	0.1567	1.175	0.3317	0.951	0.0637	0.975	0.0656

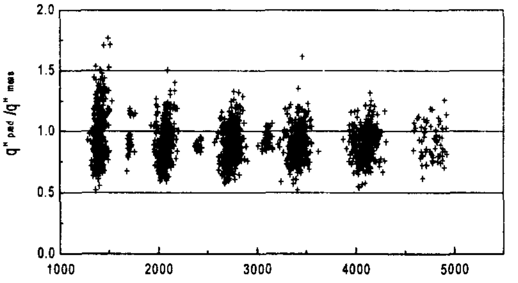
Table 3. The Evaluation of the Correction Factors for Bundle Specific Effects

	No. of Data	Without Correction		With Correction	
		Mean	Standard Dev	Mean	Standard Dev
Spacer grid Effect	639	0.892	0.1717	0.948	0.1769
Cold wall Effect	806	1.051	0.1474	0.885	0.1298
Axial heat flux Effect	64	1.081	0.1299	0.981 *1)	0.1382 *1)
				0.868 *2)	0.1685*2)

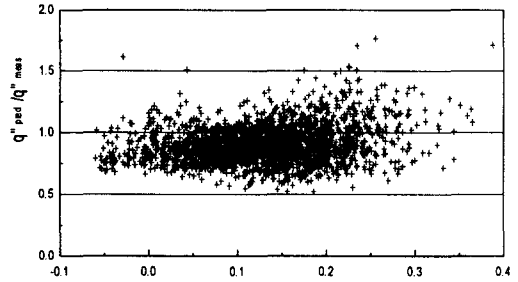
*1): Tong's F-factor, *2): Groeneveld's K_5 by boiling length averaged heat flux



(a) Pressure [Bar]



(b) Mass Flux [Kg/m²s]



(c) Quality

Figure 1. Parametric Trends of Look-Up Table Prediction by DSM

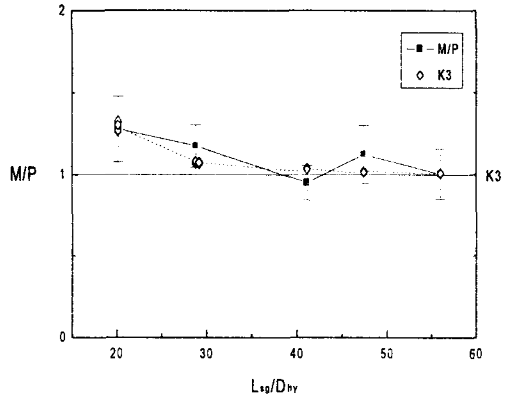


Figure 2. K3 and M/P Distributions with the Variation of L_{sg}/D_{hy} for Grid Span Effect

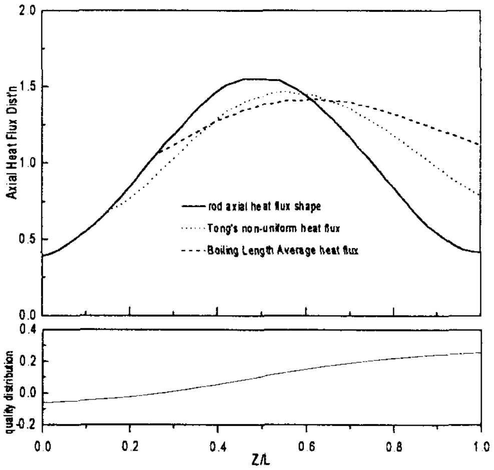


Figure 3 Equivalent Axial Heat Flux Distributions Based on Tong F-Factor and Boiling Length Average Heat Flux