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Comparative Study of Critical Heat Flux Prediction Methods

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Abstract

This paper discusses two methods for building up the empirical CHF correlation, Direct Substitution Method (DSM) and Heat Balance Method (HBM). It also includes considerations on the CHF margins, which can be expressed differently depending on the correlation types in use. Some findings are presented with exemplary calculations.

I. Introduction

The Critical Heat Flux (CHF) margin, representing the distance from an operating heat flux to the CHF, has been one of the major concerns to many researchers. Traditionally the margin, for the low-quality region, has been expressed in terms of the CHF Ratio (CHFR) or more generally the Departure from Nucleate Boiling Ratio (DNBR) which can be determined by use of the correlation based on the Direct Substitution Method (DSM). Reported papers[1),2)] show that the correlations based on the Heat Balance Method (HBM) correlate the CHF data with a better statistical advantage than those based on the DSM. It also has been pointed out by many investigators[2),3),4),5)] that the HBM approach may be a more appropriate tool for expressing a margin to CHF. These arguments stimulate us to investigate characteristics and applicability of the correlations based on two methods.

We will give a short description of how the empirical CHF correlation is built up in each method, and succeedingly compare the two types of correlations through exemplary calculations for: 1) capability of correlating the CHF data with a statistical advantage, 2) appropriateness for estimating the margin to CHF, and 3) applicability to design and analysis.

II. Description of Correlations

Two major types of CHF correlations for the subcooled or low quality region have been proposed. The first type has the form:

$$q''_{CHF} = f(G, x, p, R), \qquad (1)$$

where G, x, p and R represent for local mass flux, local quality, pressure and geometric parameters respectively. In this case, the well-known form for Eq. (1) is:

$$q''_{CHF} = A - Bx, \tag{2}$$

where A and B are functions of G, p, and R. This type of correlations, such as W-3[6], B&W-2[7], and CE-1[8], etc., are built up based on the local thermal-hydraulic condition. In this paper these will be called the DSM-based correlations because the calculated or experimental local condition is directly substituted into the correlation.

If local quality, x, is eliminated by incorporating the heat balance along the channel up to the point of interest, z, the CHF correlation takes the form

$$q''_{CHF} = f(G, x_{in}, p, \frac{x - x_{in}}{q''}; R), \tag{3}$$

where x_{in} and q'' are inlet quality and local heat flux respectively. This type of correlations will be called the HBM-based correlation in this paper because the global heat balance from inlet to outlet is taken into account. The representative type of this equation is the EPRI generalized correlation[9]:

$$q''_{CHF} = \frac{A' - B'x_{in}}{1 + \frac{B'(x - x_{in})}{q''_l}}, \tag{4}$$

where A' and B' are functions of G, p, and R. Other examples of this type are the WSC-2[10] and PI-2 correlations,[11] etc.

III. Correlating Capability

We intend to compare the capability of two types of correlations in correlating the CHF data. Assume that two coefficient functions, A and B, in Eq. (2) are the same as A' and B' in Eq. (4). Note that at the CHF condition, q''_l in Eq. (4) approaches q''_{CHF} and then Eq. (4) becomes Eq. (2). When we build up a least-square correlation by regression technique, the CHF predicted by the correlation is related to the experimental CHF data as:

$$q''_{m,i} = q''_p + \varepsilon_i, \tag{5}$$

where $q''_{m,i}$ is the i-th measured CHF, q''_p the CHF predicted by the correlation, such as Eq. (2) or (4), and ε_i the i-th regression error. Let's assume that a CHF correlation is the EPRI generalized correlation. Then Eq. (5) becomes:

$$q''_{m,i} = q''_{p,HBM} + \varepsilon_{i,HBM}, \tag{6}$$

where $$q''_{p,HBM} = \frac{A - Bx_{in}}{1 + \frac{B(x - x_{in})}{q''_{m,i}}}.$$

On substituting Eq. (6) into Eq. (5) and arranging for $q''_{m,i}$,

$$q''_{m,i} = q''_{p,DSM} + \varepsilon_{i,HBM}\left[1 + \frac{B(x - x_{in})}{q''_{m,i}}\right], \tag{7}$$

where $q''_{p,DSM}$ is the DSM-based correlation. The residual errors by each method can be related as follows:

$$(\sum \varepsilon_i^2)\mid_{DSM} \doteqdot (\sum \varepsilon_i^2)\mid_{HBM} + (\sum \varepsilon_{i,HBM}^2 \frac{2B(x-x_{in})_i}{q''_{m,i}}), \tag{8}$$

where the second-order term is neglected. Thereby the last term in Eq. (8) makes the residual errors in the DSM approach larger than those in the HBM approach.

In order to justify this, let's take an example with two correlations: a DSM-based, CE-1 correlation and a HBM-based, EPRI correlation. Only three of six test sections used in the development of the CE-1 correlation[8], were chosen for this purpose: they consisted of 21 rod with 7 ft heated length, 25 rod with 7 ft heated length, and 21 rod with 12.5 ft heated length, representing the 16x16 standard fuel assembly with 14.3" grid spacing and axially uniform heat flux. Local subchannel conditions at the subchannel exit where the DNB occurred were calculated by the COBRA-IV-i code[12]. Only the first CHF occurrences on one of nine central rods were taken into account for regression analysis: that is, the local condition only at the subchannel with the thermocouple indicating the first CHF was used for optimization of the coefficients in a CE-1 or EPRI correlation form. Looking into the selected CHF data for the test sections, the first CHFs occurred only at the matrix subchannels. Neglecting the hydraulic diameter term, the A and B of Eq. (2) can be expressed with the terms which were employed in the CE-1 correlation:

$$A = b_1(b_2 + b_3 P)\left(\frac{G}{10^6}\right)^{b_4+(b_5-b_6)P-b_7G/10^6} \quad \text{and} \quad B = b_1\left(\frac{G}{10^6}\right)^{1-b_6P-b_7G/10^6} h_{fg}.$$

The A' and B' of Eq. (4) are defined as the same form. Table 1 shows comparisons between the coefficients, b_1 to b_7 and the statistical data obtained by regression analysis. For the same set of data, we built two nonlinear least-square equations, one in a CE-1 form and the other in a EPRI form. Building up the correlation in a EPRI form leads to a smaller standard deviation of the ratio of the measured-to-predicted CHFs (M/P) than one with a CE-1 form. Distribution of residual errors in both cases (here normalized for discrete data) are shown in Figure 1. The square sum of errors for each case, with those for the last term of Eq. (8) contributing to the increased DSM errors are shown in the same figure. Therefore, we can tell that addition of heat balance parameters helps describing better the CHF characteristics in the steady state CHF test where the global heat balance is maintained.

IV. Margin Estimator

One of the well-known margin estimators, the critical heat flux ratio (CHFR) is defined as the ratio of the predicted CHF over the operating heat flux. The CHFR, when it is determined by HBM is often designated the critical power ratio (CPR), defined as the predicted critical power over the operating power, because especially for an isolated channel it equals to the CPR. Although the CHFR does not exactly match the CPR for rod bundles where interchannel flow and thermal mixing exist, the CHFR calculated by the EPRI correlation is very close to the CPR, as shown in Figure 2, while the CHFR calculated by the CE-1's is higher between channel ends than the CPR. This is resulted from one of the CHF data for a 21 rod, 7 ft heated length test section: inlet coolant temperature of 565 °F, pressure of 2000 psia and average mass velocity of 1.960 Mlbm/hr-ft^2. Similar observations were repeated for other cases. One of those is shown on Figure 3 for one of the CHF data for a 21 rod, 12.5 ft heated length test section: inlet coolant temperature of 541 °F, pressure of 2305 psia and average mass velocity of 2.510 Mlbm/hr-ft^2. The CHFR calculated by W-3 correlation, a DSM-based correlation, is included in this figure for reference. It is shown in Figures 2 and 3 that difference between the CHFRs calculated by two correlations becomes larger in the longer heated length. This implies that the margin to CHF is affected by the fluid condition upstream of the CHF location, but in the CE-1 correlation it can not be described well.

In order to evaluate the behavior of two correlations at channel exit, the CHF values were plotted on Figure 4 by varying only local quality at fixed condition given just above. This figure gives a suggestive result: If we do not calculate the local quality exactly at the CHF location and/or the CHF data distribution for local quality are not even over the applicable parameter range, the DSM-based correlation error in predicting the CHF tend to become substantially larger than the HBM's. In the DSM approach local quality is considered as a key parameter, largely contributing to estimation of CHF. Nevertheless, distribution of the CHF data over local quality, often expressed in terms of M/P or its reciprocal, etc., has been beyond general attention.

V. Applicability

Based on investigation of both CHF correlation forms, the use of the HBM seems better and more desirable in predicting the CHF. However the HBM approach has an unavoidable limitation for applying to various reactor operating conditions: highly localized CHF, where global heat balance across the coolant channel is not maintained, will not accurately be predicted by the HBM-based correlations. If it is not the case, the use of the HBM is rather recommendable. Two calculations for total loss of flow situation, where we assume that global heat balance is maintained, were performed only for exemplary purpose and these results are given in Figure 5. The initial condition of inlet coolant temperature of 564.5 °F, pressure of 2280 psia and average mass velocity of 2.630 Mlbm/hr-ft^2, and a simplified rod array, 21 heated rod with 12.5 ft heated length were chosen. At each statepoint, the minimum CHFR calculated by the EPRI correlation were significantly lower than that by the CE-1's. If we assume that the CHFR calculated by the EPRI correlation are close to the CPR as seen in the previous section, the CE-1 correlation overestimates the margin to CHF at each statepoint. Figure 6 shows the calculated results for the initial condition so overpowered that the minimum CHFR may reach 1.0 at 3 sec after the transient. The minimum CHFR calculated with the CE-1's decreases with a steep slope at CHFR-time space and then reaches 1.0. Therefore, designs and analyses by the DSM-based correlations may provide an inadequate information of the CHF margin.

For now, the DSM approach seems to be more effective for extended applications to reactor operating conditions, while the HBM approach is fascinating from a viewpoint of predicting the CHF more realistically, especially in the other boiling systems where the system power capability is more important than the localized CHF phenomena as well as in the reactor power uprating study. A persuasive alternative for alleviating the weakness of the DSM-based correlation is to build up a correlation which behaves as the HBM's by introducing the partial heat balance, taking into account the effects of upstream conditions to some extents. This will decrease the dependency of CHF on local quality, milder slopes in q''-x space on Figure 3. However, it may be far from the final resolution.

VI. Concluding Remarks

Two methods for correlating the experimental CHF data are discussed: the DSM and HBM. By the use of the HBM-based correlations the CHF data can be correlated with better statistical advantage and the margin to CHF can be estimated more reasonably. While the use of the HBM is limited to the conditions where global heat balance is maintained, the use of the DSM could be still more effective for extended application to reactor operating conditions. However, it needs to be noted that the possibility for CHF error by DSM-based correlations in predicting the CHF is substantially larger than by HBM's in case where the CHF data is insufficient and uneven over the applicable parameter range. Finally the problems, which method is more appropriate for reactor design and analysis, remain to be studied further.

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Table 1. Regression Results for CE-1 and EPRI Correlation Forms

Coefficients / Correlation Form	b_1 ($x10^{-3}$)	b_2	b_3 ($x10^{-2}$)	b_4	b_5 ($x10^{-4}$)	b_6 ($x10^{-4}$)	b_7 ($x10^{-2}$)
CE-1 and	2.6002	408.06	-9.7806	-.67784	6.7535	2.8403	-8.3146
M/P Statistics	No. of data =169, mean = 1.0004, standard dev. = 0.059683						
EPRI and	2.6440	407.08	-9.8105	-.68118	6.6875	2.7737	-8.3107
M/P Statistics	No. of data =169, mean = .99978, standard dev. = 0.024354						

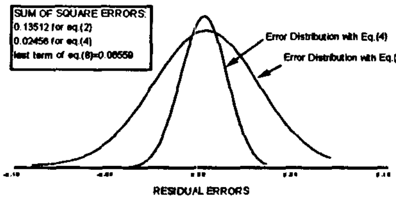

Figure 1. Residual Error Distributions

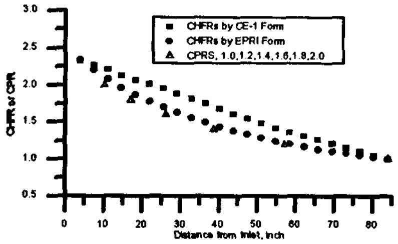

Figure 2. Comparison of CHFR by DSM- and HBM-Based Correlations

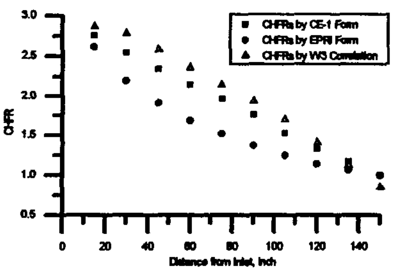

Figure 3. Comparison of CHFR by DSM- and HBM-Based Correlations

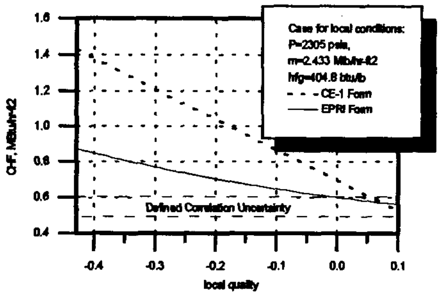

Figure 4. CHF versus Local Quality at Fixed Conditions

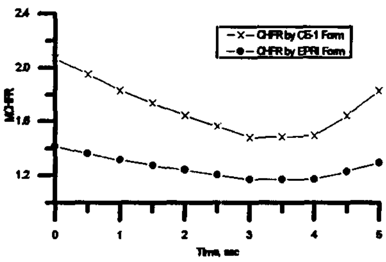

Figure 5. CHFR Behavior for Loss of Flow (nominal case)

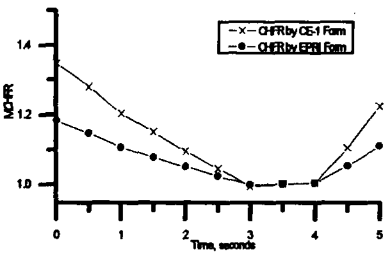

Figure 6. CHFR Behavior for Loss of Flow (overpower case)