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On the Application of Correction Factor for Axial Power Distribution to CHF Correlation Development

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1. Introduction

The axial heat flux distribution in nuclear reactors is invariably non-uniform. Thus it is very important to validate the general applicability of CHF correlation developed with limited types of axial heat flux distribution to actual situation of various axial power shapes in reactor operation. Per the recent fuel development, CHF testing is performed for chopped cosine axial heat flux distribution only. Thus it is inevitable to re-clarify the validity of correction factor for non-uniform axial heat flux distribution to support the general applicability of CHF correlation developed with data recently tested.

Two ways of approach are considered to care the effects of axial power distribution in CHF correlation development. With the first method, CHF correlation is developed based on the data of uniform axial heat flux distribution only. To apply the correlation to the data of various axially non-uniform heat flux distribution, a factor such as Tong's F-factor [1] is applied to the predicted value by the correlation itself to correct the effects of upstream memory on CHF. With the second approach, CHF correlation is developed based on whole data with the concept of equivalent uniform heat flux for the data of non-uniform axial heat flux distribution. The equivalent uniform heat flux is a measured CHF value for the data of uniform axial heat flux distribution, but it is a pseudo-CHF with a corrective factor for the data of non-uniform axial heat flux distribution. The corrective factor is applied to predict CHF for any non-uniform axial heat flux distribution.

2. Concept of Correction

The effects of axial power distribution on CHF can be expressed by two methods. The one is the way of additive or deductive and the other is the way of ratio. The latter is prepared to actual application as ;

$$F \equiv \frac{q''_U}{q''_{NU}(z_{CHF})} \tag{1}$$

2.1 Local Condition Hypothesis

If it is assumed that there is a unique relationship between CHF and local quality, then the case of a non-uniform heated tube can be dealt with in a straight-forward manner. The level of critical mean heat flux (or power) is that which, for any locality within the channel, causes the unique CHF/quality relationship to be the first satisfied. For a purely valid situation of local condition hypothesis, correction factor is unity, i.e.,

$$q''_{NU}(z_{CHF}) = q''_U \tag{2}$$

But it is failed to give general validness per various axial power distribution.

2.2 Overall Power Hypothesis

As alternative method of local condition hypothesis, it is assumed that the total power which can be fed with non-uniform heating will be the same as for a uniformly heating with the same inlet condition in overall power hypothesis. That is,

$$\int_0^{z_{CHF}} q''_{NU}(z)\,dz = \int_0^{z_{CHF}} q''_U\,dz \tag{3}$$

Thus correction relationship can be expressed by

$$F = \frac{\int_0^{z_{CHF}} q''_{NU}(z)\,dz}{q''_{NU}(z_{CHF}) \cdot z_{CHF}} \equiv Y\left(z_{CHF}\right) \tag{4}$$

It is found that overall power hypothesis is good for symmetric power profile.

2.3 Tong's F Factor

A consequence of failure of the local condition hypothesis and limitation of overall power hypothesis for the effects of non-uniform flux distribution on CHF is that the value of the local CHF must depend, to some degree, on the heat flux profile of the point considered. The relationship is derived by considering an energy balance on the super heated boundary layer in the bubbly flow region. The ratio of heat flux with the same local enthalpy for uniform and non-uniform flux profile is given by

$$F = \frac{C}{q''_{z_{CHF}}(1 - e^{-C \cdot z_{CHF}})} \int_0^{z_{CHF}} q''(z) \cdot e^{-C \cdot (z_{CHF} - z)} dz \tag{5}$$

Tong's F factor is verified with the data of various axial power distributions [1] and widely used with the expression of C determined via empirical data as

$$C = 0.15 \cdot \frac{\left(1 - X_{z_{CHF}}\right)^{4.31}}{\left(G_{z_{CHF}}/10^6\right)^{0.478}} \text{ [1/inch]} \tag{6}$$

for a rod bundle [2].

3. Verification of Hypotheses

3.1 Local Condition Hypothesis

As described in section 2.1, there is a limitation to apply local condition hypothesis to measure the effects of non-uniform axial power distribution on CHF. But it gives basic idea of transformation to equivalent-uniform CHF regardless of CHF location. The results of data comparison shown in Figure 1 give the validity of local condition hypothesis. The data in Figure 1 are differed only heated length ("S" = Short, "L" =Long). The concept of equivalent enthalpy rise (Delta-H EQ) by heated length is introduced with modification of equivalent inlet enthalpy per reference 3. The data falling in same straight line mean that there is a unique relationship between CHF and enthalpy rise.

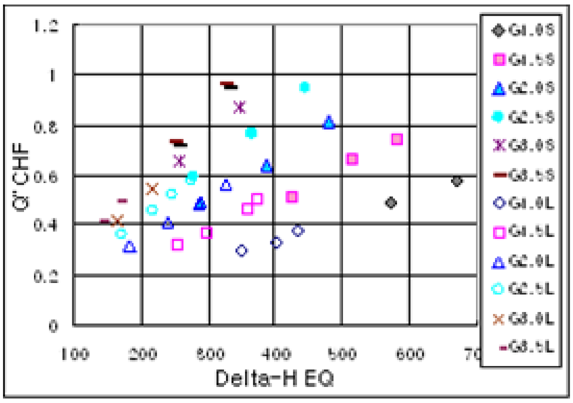

Figure 1 CHF Data Comparison : Different Heated Length

3.2 Overall Power Hypothesis/Tong's F Factor

The effects of different axial power distribution can be measured with the concept of generalized equivalent enthalpy rise (Delta-H/zFz) as given in Figure 2. Additional term, zFz, is introduced to express the characteristics of enthalpy rise for non-uniform axial power distribution. The data in Figure 2 are differed only axial power distribution ("C" = Cosine, "L" = Uniform). The same as local condition hypothesis, the data falling in same straight line mean that there is a unique relationship between CHF and corrected enthalpy rise. Thus the method applied is valid enough to correct the effects of different axial power distribution. At the fixed local condition two concepts of this section are equivalent.

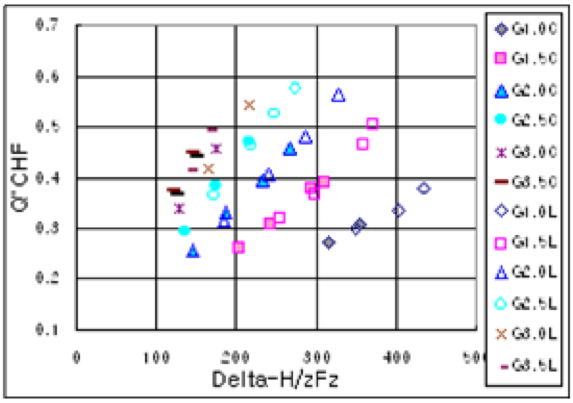

Figure 2 CHF Data Comparison : Different Axial Power Distributions

4. Application of Correction Factor to CHF Correlation Development

As described in section of "Introduction," there are two different ways to develop CHF correlation with the data of various axial power distributions. The CHF correlations developed with the first method are CE-1 [4], EPRI-1 [5], WRB-1 [4] etc. Ideally, kinds of axial power distribution should be various enough to simulate any possible power distributions properly. However, limited non-uniform power distributions are generally considered as symmetric chopped cosine and skewed toward top/bottom with peak to average ratio around 1.5. The statistics or performance of the correlation, however, is generally expressed for all data engaged in database. The CHF correlations developed with this method are W-3 R [4], WRB-2 [4], WRB-2M [4], etc. KCE-1 [4] has been developed with non-uniform axial powered data only but not to apply the concept of equivalent uniform. It is no doubt to use whole data to derive statistics of correlation developed with this approach.

The comparison of results with the CHF correlations which developed different approach in data of non-uniform axial power distribution may give physical evidence to show that both approaches are valid and equivalent. The matched data between W-3 R correlation (second approach) and WRB-1 correlation (first approach) are compared as given in Figure 3. Majority of data is within +/- 20% bandwidth per measured CHF and predicted CHF plane. There is no inherent difference in results between axial power shapes ("C" = Cosine, "T" = Top Skewed) and between CHF correlations. Note that there are more data above the dashed blue line for WRB-1 results and it is conservative.

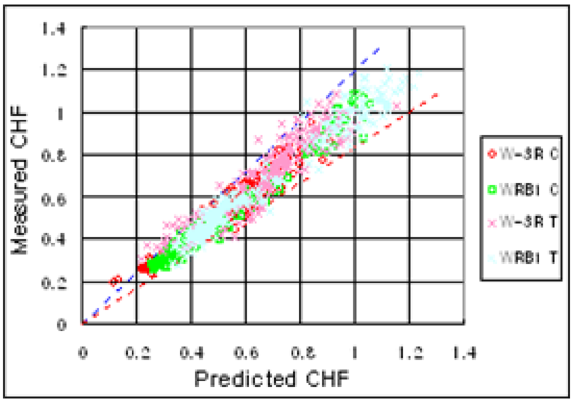

Figure 3 Comparison of Results with Different Approaches

5. Conclusion

Review of correction methods including basic concepts is performed. The direct comparison of CHF data with concept of Delta-H/zFz for different axial power shapes and the assessments with CHF correlation for matched data per different development approaches show basis for the general applicability of correction factor which developed with test data of variety axial power distribution. Thus it is expected that there is no critical restriction to actual application of CHF correlation developed with limited axial power shapes (especially cosine non-uniform).

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