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# Effect of Correlation Uncertainty Distribution on Design Limit CHFR

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## 1. Introduction

In general, the minimum critical heat flux ratio (MCHFR) is the key parameter determining the fuel integrity of research reactor. Usually, the design limit CHFR is evaluated deterministically with the correlation uncertainty alone, and the actual CHFR of the fuel is estimated conservatively determined with a hot channel factor (HCF) to consider the uncertainty of the heat flux from the fuel.

On the other hand, the design limit CHFR can be determined statistically incorporating the uncertainty of heat flux with the correlation uncertainty, and then the actual CHFR of the fuel can be calculated as is without the HCF. This approach gives clear insight about the probabilistic information, and also decreases unnecessary conservatism of estimation.

The statistical determination of design limit CHFR depends primarily on the distribution of correlation uncertainty, which is assumed on the actual experimental data. Since the experimental data does not coincide with the ideal distribution of normal or uniform, the proper assumption on the distribution is critical for the statistical determination of design limit CHFR.

In this paper, the effect of the correlation distribution assumption on a design limit CHFR is examined for two different CHF correlations, Mirshak and Kaminaga.

## 2. Analysis Methods

The design limit CHFR is determined statistically with the distribution of uncertainty parameters affecting the heat flux and the correlation. The uncertainty parameters affecting the design limit CHFR are selected first, and the random distribution of normalized CHFR is formulated for the parameters. The design limit CHFR is then determined from the distribution with respect to the tolerance limit. The detailed procedures of the determination are as follows.

Table 1 shows the parameters related to the determination of design limit CHFR. The distribution of each parameter is evaluated from the actual measurement, or assumed when the actual measurement is not provided. The unknown distribution of uncertainty parameters is assumed as uniform over the uncertainty range, which results in more conservative results of design limit CHFR.

Once the uncertainty parameters are selected and their distribution is evaluated, the distribution of random normalized CHFR can be formulated with the uncertainty parameters as [1]

$$\frac{CHFR_n}{CHFR_r} = \frac{\psi_n F_1 F_2 F_3 F_4}{\psi_r} \qquad (1)$$

where $\psi_n$ is the CHF value calculated with the nominal parameters required for the correlation, and $\psi_r$ is the random CHF value with the random parameters. The correlation factor $F_4$ can be either at the numerator or at the denominator depending on the definition of the correlation uncertainty: defined for measured/predicted or predicted/measured. Here, the factor is defined for predicted/measured.

The design limit CHFR is then determined from the distributed random normalized CHFR, by selecting Z as

$$P\left(\frac{CHFR_n}{CHFR_r} < Z\right) = p\ , \qquad (2)$$

where $p$ is the tolerance limit, assumed 95% in this analysis. The distribution of the random normalized CHFR is constructed by Monte-Carlo method, with random sampling of uncertainty parameters. One million samples are generated for each uncertainty parameter following their distribution, and combined with Eq. (1).

The most important parameter among those in Table 1 is the uncertainty of CHF correlation, because it is usually much larger than the other parameters. Therefore, proper assumptions are critical for the determination of design limit CHFR. The uncertainty are estimated for two different CHF correlations widely used for research reactors with plate type fuel, which are Mirshak [2] and Kaminaga [3] correlation.

Figure 1 shows the uncertainty distribution of Mirshak correlation estimated from the raw data found from the reference. The distribution seems similar to uniform and far from normal. The hypothesis of normality on the distribution is rejected by D' test with confidence level of 95% [4], therefore the distribution cannot be assumed as normal with its original standard deviation. Instead, two different distributions are assumed on Mirshak correlation uncertainty: one for normal and the other for uniform. The normal distribution is assumed such that the lower 95% of the data is included in the lower 95% of the normal distribution because the sample standard deviation from the raw data is not applicable. When the distribution is not normal by D' test, the limit value of the CHFR correlation is usually set by this method. However, the normal distribution still cannot envelope the sample distribution of the correlation, a uniform distribution is assumed on the distribution. The uniform distribution enveloping the correlation uncertainty has upper and lower limit of $\pm 0.16$.

The uncertainty information of Kaminaga correlation is given in the reference as 33% with one-sided 95% tolerance level [3] for the uncertainty defined for measured/predicted values, however, the uncertainty information for predicted/measured is absent. The uncertainty distribution defined for predicted/measured is then constructed from the digitized data from the figures in the references [3, 5].

Figure 2 shows the uncertainty distribution of Kaminaga correlation with the uncertainty defined for predicted /measured. The distribution is normal with 95% confidence level following to the D'test result, therefore, the distribution is assumed as normal with its original standard deviation.

The above standard deviations of uncertainty distributions in Mirshak and Kaminaga correlations are estimated for sample (s), and then the standard deviation of population ($\sigma$) are estimated considering the sample size and the confidence level.

The standard deviation of population can be estimated as

$$\sigma = \frac{k}{k_\infty} s \tag{3}$$

where $k_\infty$ and $k$ are the tolerance limit of population and sample, respectively [6].

## 3. Results

Figure 3 shows the distribution of normalized random CHFR with Mirshak correlation with respect to the assumption on the uncertainty distribution of the correlation. Although the assumed distribution of correlation uncertainty are totally different each other, the estimated random CHFR distribution are quite similar both case. Usually, the uniform distribution of uncertainty parameter yields the resulting distribution of random normalized CHFR become wider at the middle, which causes the design limit CHFR become larger. However, the effect is not shown with Mirshak correlation since the correlation uncertainty is relatively smaller than the other correlations such as Kaminaga. Due to the small difference between two cases, the design limit CHFR are also almost identical regardless of the assumption on the distributions. Although the two case with different distribution on the correlation uncertainty gives almost similar results in design limit CHFR, the uniform distribution makes better fit on the experimental data, therefore is recommended for this case.

Figure 4 shows the distribution of normalized random CHFR with Kaminaga correlation, with respect to the definition on the uncertainty either for measured/ predicted or predicted/measured. The distribution with the definition for measured/predicted are based on the uncertainty supplied from the reference, shows narrower shape, however, seems inverse Gaussian rather than normal. Since the inverse Gaussian distribution shows right-tailed shape, the design limit CHFR estimated at the right tail of the distribution tend to become larger. Eq. 1 shows that the correlation uncertainty defined for predicted/measured yields the uncertainty factor placed at numerator, which can avoid the distribution from being inverse Gaussian. Since the normal distribution for predicted/measured data of Kaminaga correlation can be assumed by D' test and the assumption avoids the skewed distribution of random normalized CHFR, the is recommended for Kaminaga correlation.

Table 2 shows the summary of the design limit CHFR for different assumptions of correlation uncertainty distributions. Overall, the uniform distribution on Mirshak correlation and the uncertainty defined for predicted/measured of Kaminaga correlation are recommended assumptions for estimating statistical design limit CHFR.

## 4. Conclusion

The design limit CHFR is estimated for different CHF correlations and different assumptions on the uncertainty distributions. Mirshak and Kaminaga correlation are selected as the CHF correlation and the design limit CHFR are estimated for them.

The uncertainty distribution on Mirshak correlation is more similar to uniform than normal, therefore the uniform assumption on the distributions gives proper estimation on design limit CHFR with the correlation. The uncertainty of the correlation need to be defined for predicted/measured since the formulation of random normalized CHFR has the correlation uncertainty factor at the numerator. Defining the uncertainty for predicted/measured, the uncertainty distribution of Kaminaga correlation can be assumed as a normal distribution, and the design limit CHFR is less conservatively estimated comparing to that defined for measured/predicted.

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Table 1 Parameters affecting design limit CHFR

| Uncertainty | Factor | Distribution |
|---|---|---|
| Reactor power measurement | $F_1$ | Uniform |
| Power density calculation | $F_2$ | Uniform |
| U235 homogeneity | $F_3$ | Normal |
| CHF correlation | $F_4$ | Normal or Uniform |

Table 2 Summary of design limit CHFR

| Correlation /Assumptions | Design limit CHFR (95% tolerance level) |
|---|---|
| Mirshak (Normal Dist.) | 1.267 |
| Mirshak (Uniform Dist.) | **1.262** |
| Kaminaga ($F_4$ :measured/predicted) | 1.578 |
| Kaminaga ($F_4$ : predicted/measured) | **1.508** |

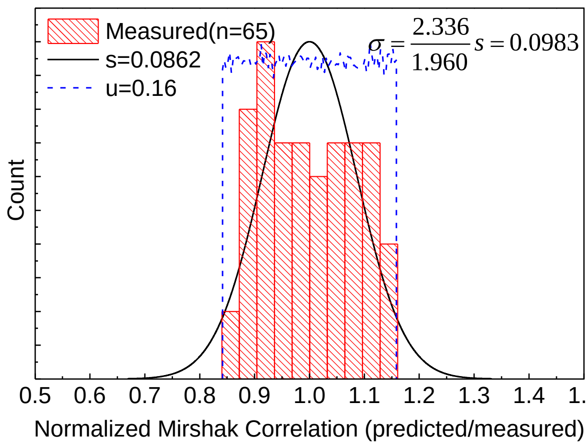


Fig. 1 Uncertainty distribution of Mirshak correlation

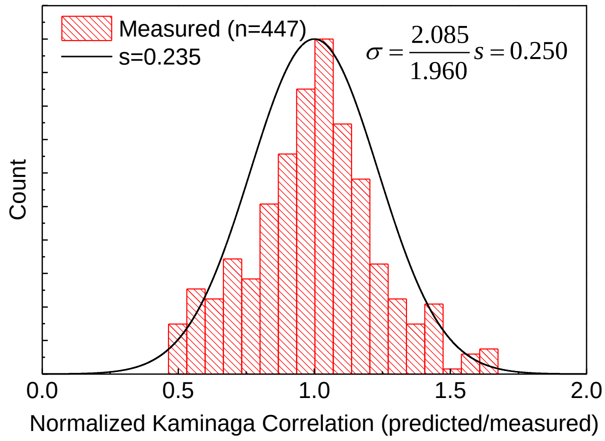


Fig. 2 Uncertainty distribution of Kaminaga correlation

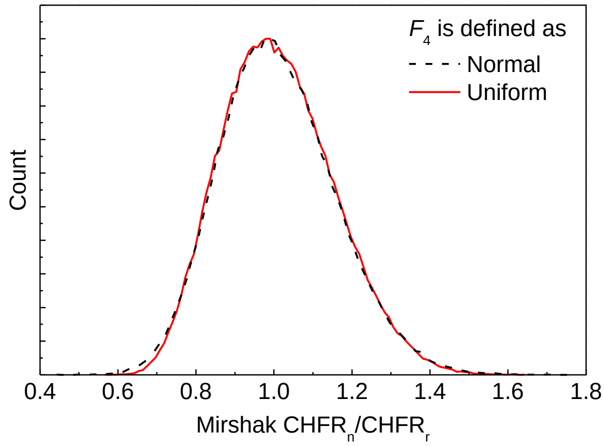


Fig. 3 Distribution of normalized random CHFR with Mirshak correlation

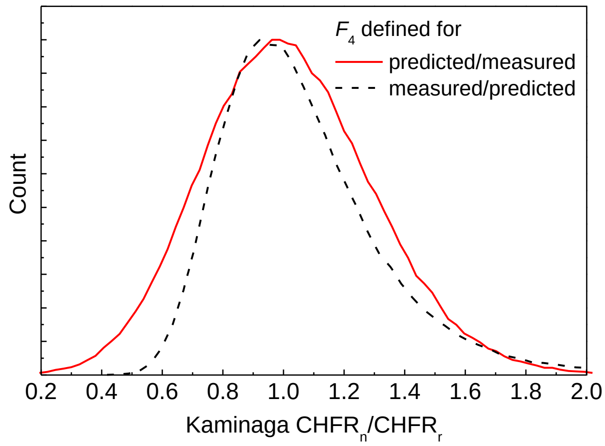


Fig. 4 Distribution of normalized random CHFR with Sudo-Kaminaga CHF correlation