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Statistical Hot Channel Factors and Safety Limit CHFR/OFIR

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1. Introduction

The fuel integrity of research reactors are usually judged by comparing the critical heat flux ratio (CHFR) and the maximum fuel temperature (MFT) with the safety limits. Onset of flow instability ratio (OFIR) can also be used for the examination with CHFR. Hot channel factors (HCFs) are incorporated when calculating the CHFR/OFIR and MFT, to consider the uncertainties of fuel properties and thermo-hydraulic variables affecting them.

The most of HCFs used for the safety analyses are estimated deterministically, combining uncertainties by simple multiplications or root-sum-squares. Also, the safety limit CHFR/OFIR is evaluated deterministically by multiplicating the relative HCF to the heat flux. The HCFs and safety limit CHFR is sometimes estimated to include too much conservatism, deteriorating the design flexibilities and operating margins.

In this paper, a statistical estimation of HCFs and the safety limit CHFR/OFIR is presented by a random sampling of uncertainty parameters. A 15MW pool type research reactor is selected as the sample reactor for the estimation.

2. Analysis Methods

Three HCFs are used for evaluating the maximum fuel temperature and critical heat flux ratio, which are the safety parameters for fuel integrity. The maximum fuel temperature is calculated as

$$T_{f,hc} = T_{in} + F_b(T_b - T_{in}) + F_f(T_w - T_b) + F_q(T_f - T_w) \quad (1)$$

where F_b, F_f and F_q are the hot channel factors related to bulk temperature rise, film temperature rise, and heat flux, respectively. And the subscript of in, b, w and f mean inlet, bulk, wall, and fuel, respectively. The critical heat flux ratio is also calculated with introducing F_q in deterministic manner. In a deterministic way, each HCF is calculated by multiplications or root-sum-squares of affecting parameter uncertainties such as channel dimensions, fuel loadings, and measurement uncertainties.

In a statistical way, however, the distributions of each parameter are evaluated by measurements or assumptions, and the HCFs are estimated from the combination of the parameter distributions. The design limit CHFR including uncertainties of relative parameters is presented in a statistical way, whereas the design limit CHFR with correlation uncertainty and the F_q are used separately in a deterministic way.

Table 1 shows the parameters and their uncertainties affecting the estimation of HCFs and safety limit CHFRs. The uncertainty distribution of channel dimensions and U235 contents in the fuel are evaluated from the measurement of test fuel assemblies for a 15MW pool type research reactor, and the measurement uncertainties and the calculation uncertainties are estimated from instrumentations and designs. The distribution of correlation uncertainties are from the measurement data from references [1-4]. When the uncertainty is given with upper and lower bound without the shape of distribution, the distribution is assumed to be uniform. The pressure measurement uncertainty is set to zero since it is not measured during reactor operation.

When determining the distribution of the parameters, the standard deviations (σ) need to be calculated considering the sample size as well as the distribution of sample. When the sample size is finite, the standard deviation of parent population is calculated from the standard deviation of sample, confidence level, and the sample size as

$$\sigma = \frac{k}{k_\infty} s \quad (2)$$

where σ and s are the standard deviation of parent population and sample. k_∞ and k are the tolerance parameter of parent population and sample, respectively. The k value is determined by the sample size and the confidence level, as well as the tolerance.

The three HCF factors in Eq. (1) is then calculated from the parameter uncertainties as [6]

$$F_b = \frac{F_1 F_2 F_8}{F_5 F_6 F_4^{5/3}} \quad (3)$$

Table 1 Parameters and uncertainties affecting HCFs and safety limit CHFRs.

Uncertainty	Factor	Distribution
Reactor power measurement	F_1	Uniform
Power density calculation	F_2	Uniform
Local channel tolerance	F_3	Normal
Average channel tolerance	F_4	Normal
Velocity distribution measurement	F_5	Uniform
Flow rate measurement	F_6	Uniform
U235 homogeneity	F_7	Normal
U235 loading per plate	F_8	Normal
Pressure measurement	F_9	0
Heat transfer correlation	F_{10}	Normal
CHF/OFI correlation	F_{11}	Normal

$$F_f = \frac{F_1 F_2 F_3 F_7}{F_{10} F_4^{1/3} F_5^{0.8} F_6^{0.8}} \qquad (4)$$

$$F_q = F_1 F_2 F_7 \qquad (5)$$

Here, the HCFs are calculated as distributions, and then the actual HCF values are selected with certain tolerance levels such as 90%, 95% and 99.9%.

The CHFR and OFIR value can be calculated similarly. However, the ratio of distributed value per nominal value needs to be evaluated statistically because the correlation for CHF and OFI are usually not a simple function as expressed in Eq. (3) to (5). Then, the relative CHFR and OFIR become

$$\frac{CHFR_n}{CHFR_r}\left(or \frac{OFIR_n}{OFIR_r} \right) = \frac{\psi_n F_{11} F_1 F_2 F_7}{\psi_r} or \frac{\psi_n F_1 F_2 F_7}{\psi_r F_{11}} \qquad (6)$$

where ψ is the CHF or OFI correlation at a given condition, and subscript r and n mean distributed and nominal value, respectively. Depending on the way that the correlation uncertainty defined, F_{11} is on the numerator or denominator at the left side of Eq. (6). The correlation uncertainty factor comes to numerator for Mirshak correlation, and it comes to denominator for Sudo-Kaminaga and Whittle-Forgan correlation.

The distribution of HCFs and safety limit CHFR/OFIR are then evaluated for 10000 random sample sets from the distributed parameters of Table 1. And the 95% percentile values with 95% confidence level are selected as the final HCFs and the safety limits.

3. Results

Figure 1 shows the distribution of relative CHFR by Mirshak CHF correlation. The relative CHFR is defined as $CHFR_n/CHFR_r$, and the upper 95% percentile value in the distribution, 1.42, is the safety limit CHFR used for the safety analyses. This means that the fuel integrity is ensured when the minimum CHFR is higher than 1.42 without considering any HCFs.

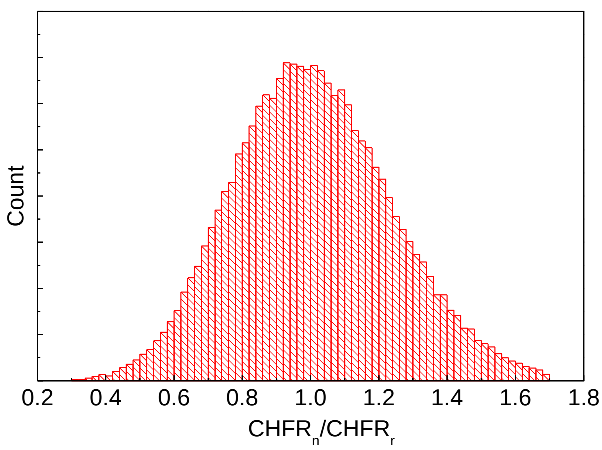

Fig. 1 Distribution of CHFR with Mirshak CHF correlation

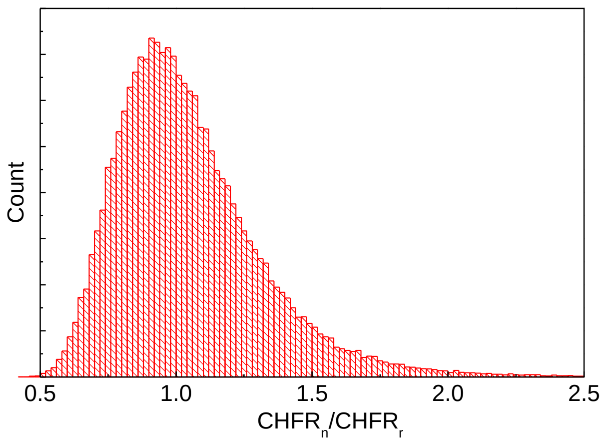

Fig. 2 Distribution of CHFR with Sudo-Kaminaga CHF correlation

Figure 2 shows the distribution of relative CHFR by Sudo-Kaminaga CHF correlation. Since the model reactor has downward flow at the core, the downflow correlation of the Sudo-Kaminaga set is used for the calculation. The 95% percentile value in the distribution is 1.56, which is the safety limit CHFR for Sudo-Kaminaga correlation with the model reactor. The relative CHFR distribution by Sudo-Kaminaga correlation shows skewed shape comparing to the that of Mirshak, because the correlation uncertainty factor of Sudo-Kaminaga correlation in Eq. (6) is at the denominator whereas it is at the numerator in Mirshak correlation.

Figure 3 shows the distribution of relative CHFR by Whittle-Forgan OFI correlation. The 95% percentile value in the distribution, 1.21, is the safety limit OFIR. Although the uncertainty factor of Whittle-Forgan OFI correlation in Eq. (6) is at the denominator as Sudo-Kaminaga correlation, the skewness of distribution is not notable as Fig. 2 because the uncertainty of Whittle-Forgan correlation is smaller than that of Sudo-Kaminaga correlation. As the result, the safety limit OFIR is smaller than those of CHFR due to the small correlation uncertainty.

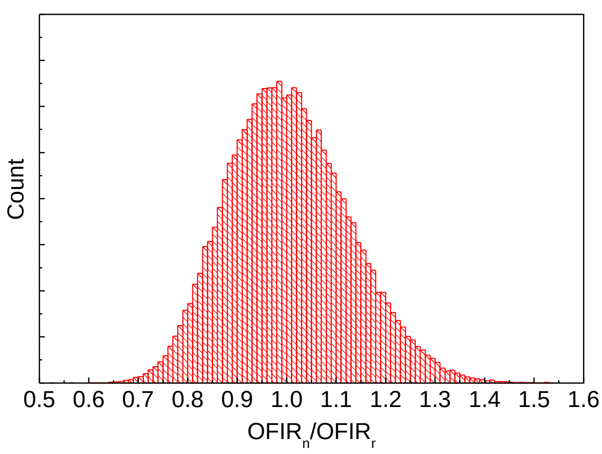

Fig. 3 Distribution of OFIR with Whittle-Forgan OFI correlation

Table 2 Summary of HCFs and safety limit CHFR/OFIR

Values	Statistic			Deterministic
	90%	95%	99.9 %	
F_b	1.14	1.19	1.34	1.28
F_f	1.43	1.62	3.31	1.51
F_q	1.13	1.16	1.30	1.25
Safety Limit CHFR (Mirshak)	1.32	1.42	1.86	1.66
Safety Limit CHFR (Sudo-Kaminaga)	1.40	1.56	2.85	1.87
Safety Limit OFIR (Whittle-Forgan)	1.16	1.21	1.41	1.26

Table 2 shows the summary of the statistical HCFs and safety limit CHFR/OFIR. The deterministic HCFs and the safety limit CHFR/OFIR is also listed in the table for comparison. The deterministic safety limits are calculated by multiplying the F_q to the correlation uncertainties which is defined as the 95% percentile value in the correlation distribution. The HCFs and the safety limit CHFR/OFIR evaluated statistically are smaller than those estimated deterministically, resulting in more margin for design and operation of the reactor.

4. Conclusion

The HCFs and the safety limit CHFR/OFIR of a 15MW pool type research reactor are evaluated statistically. The parameters affecting the HCF and the safety limit CHFR/OFIR are listed and their uncertainties are estimated. The relevant parameter uncertainties are sampled randomly and the HCFs and the safety limits are evaluated from them.

The HCFs and the safety limit CHFR/OFIR with 95% probability are smaller than those estimated deterministically because the statistical evaluation convolute the correlation uncertainties and the other uncertainties in probabilistic way, whereas the deterministic evaluation simply multiply them. The smaller HCFs and safety limits give quantitative insight in terms of probability, and secure more margin for design and operation of the reactor.

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