Prediction of Hot Channel Factor in the OPAL Research Reactor as a Reference for Plate Type Fueled Research Reactor

Junyoung Lim [a], Kiwon Song [b], Jaehyun Cho [a*]
[a]*Energy System Engineering, Chung-ang University, 84 Heukseok-ro, Dongjak-gu, Seoul, Republic of Korea*
[b]*Korea Atomic Energy Research Institute, 989-111 Daedeok Daero, Yuseong Gu, Daejeon, Republic of Korea*
[*]*Corresponding author: jcho@cau.ac.kr*

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1. Introduction

Hot Channel Factor(HCF) is one of the critical considerations in the thermal-hydraulic design of research and commercial reactors. Within a reactor, not all fuel channels share identical thermal and flow conditions. Especially in plate type fuel, due to its independently separated channels, this phenomenon is more emphasized. Such variations arise due to manufacturing tolerances of nuclear fuel, uncertainties in power and flow distribution. Consequently, certain channels exhibit more unfavorable thermal behavior than the average channel. The most conservative of these is referred to as the *hot channel,* and a conservative approach is taken by applying HCF to the average analysis results. The method for deriving and applying HCFs vary across different research reactors.

In plate type fueled research reactors, core thermal-hydraulic design and thermal margin assessment are carried out by applying the HCF which includes design uncertainties. Instead of performing thermal-hydraulic calculations for every individual fuel channel, the most conservative channel-the hot channel-is identified, and thermal-hydraulic analysis and thermal margin evaluations are then conducted under the assumption that if the hot channel satisfies the design criteria, all channels satisfies the design criteria.

The OPAL research reactor is a 20 MW open-pool multipurpose plate type fueled research reactor, designed and constructed by INVAP of Argentina, and located in ANSTO, Sydney, Australia. Since its commissioning in 2006, OPAL has remained the largest nuclear facility in Australia and one of the world's leading research reactors.

In this study, methods for evaluating HCFs in plate type fueled research reactors are analyzed, and OPAL is selected as the reference reactor for predicting HCF values. Since OPAL can achieve effective cooling with relatively low coolant flow rates compared to its heat flux[1], predicting its HCF is advantageous for optimizing thermal-hydraulic design. Therefore, the 3-factor HCF method applied to PLTEMP/ANL[2] is employed to estimate the HCF values that may have been used in OPAL's design.

2. Methods and Results

In this chapter, the method for evaluating HCF in plate type fueled research reactors are analyzed, and the approach and results of predicting the HCF for OPAL are presented.

2.1 Analysis of HCF Evaluation Method in Plate Type Fueled Research Reactor

Table I presents hot channels and uncertainty factors applied in plate-type fuel research reactors. Some of the data are uncertain due to limited resources. Although PLTEMP/ANL is not a research reactor itself, it is a thermal-hydraulic analysis code for plate-type fuel that provides hot channel factors and has been widely utilized as a valuable tool in thermal-hydraulic analyses of research reactors; therefore, it was included in this study. As shown in Table I, the types and numbers of HCFs applied vary by reactor, and the uncertainty factors considered in HCF determination also differ across reactors.

HCF is derived from the combined uncertainties associated with fuel manufacturing tolerances, power and flow distributions, measurement errors, and thermal-hydraulic correlations. As shown in Table I, these uncertainty factors are classified into random errors and systematic errors, and they are referred to as *sub-factors*. Table II describes the parameters that give rise to each type of uncertainty.

The application of sub-factors to the hot channel factor can be classified into two approaches: a statistical method using Eq. (1) and a multiplicative method using Eq. (2).

$$U = 1 + \sqrt{\textstyle\sum_i (1 - U_i)^2} \qquad (1)$$

$$U = \textstyle\prod_i U_i \qquad (2)$$

where U is the HCF derived from the combination of sub-factors, while U_i denotes the sub-factor corresponding to the uncertainty i.

The choice between the statistical method and the multiplicative method varies depending on the reactor. For example, in PLTEMP/ANL, the statistical method is applied to random error sub-factors, while the multiplicative method is applied to systematic error sub-factors. The final HCF is then determined by multiplying the HCF value obtained from the random error sub-

Table I: Hot channels and uncertainty factors applied in plate-type fuel research reactors[2,3,4,5,6]

	Research Reactor					
Plate-type Research Reactor	Name	MURR-LEU	PLTEMP/ANL	OPAL	NBSR	JRR-3M
	Country	USA	USA	USA	USA	Japan
Operating Condition	Power	10MW	-	20MW	20MW	20MW
T/H Design Data	HCF					
	HCF for heat flux	1.27	1.30	-	1.35	1.16
	HCF for bulk temperature rise	1.54	1.45	-	1.49	1.33
	HCF for film temperature rise	1.46	1.75	-	-	1.37
	HCF for Heat Transfer Coefficient	-	1.50	-	1.48	-
	HCF for flow	1.23	1.38	-	-	-
HCF Uncertainty Factors	Random Errors					
	Fuel meat thickness	O	O	O	O	O
	U-235 Homogeneity	O	O	O	O	O
	U-235 Loading per plate	O	O	O	O	O
	Power Distribution	O	O	O	O	O
	Channel Spacing	O	O	O	O	O
	Flow Distribution	O	O	-	O	O
	System Errors					
	Power Measurement	O	O	O	O	O
	Flow Measurement	O	O	-	O	O
	Heat Transfer Coefficient	-	O	O	O	O

Table II: Type of uncertainties applied to HCF

Random Errors	
Fuel Meat Thickness	Fuel plate thickness variation uncertainty
U-235 Homogeneity	Fuel plate U-235 distribution homogeneity uncertainty
U-235 Loading per Plate	Fuel plate U-235 loading uncertainty
Power Distribution	Power distribution uncertainty due to core design calculation
Channel Spacing	Coolant channel thickness uncertainty due to fuel assembly fabrication tolerance
Flow Distribution	Flow distribution instability uncertainty
System Errors	
Power Measurement	Power measure instrument uncertainty
Flow Measurement	Flow measure instrument uncertainty
Heat Transfer Coefficient	Heat transfer correlation uncertainty

Table III: EHCF of PLTEMP/ANL[2]

Uncertainty	**Type of Tolerance**	**Effect on Bulk ΔT, Fraction**	**Value**	**Tolerance**	**Tolerance Fraction**	**Heat Flux, F_q**	**Channel Flow Rate, F_w**	**Geat Transfer Coef., F_h**	**Channel Temp. rise, F_{bulk}**	**Film Temp. rise, F_{film}**
Fuel meat thickness	local				0.07	1.07				1.07
U235 homogeneity					0.20	1.20				1.20
U235 loading per plate		0.50			0.03	1.03			1.015	1.03
Power density		0.50			0.10	1.10			1.050	1.10
Channel spacing	local	1.00	0.124	0.01	1.09		1.155	1.03	1.155	1.03
Flow distribution		1.00			0.20		1.200	1.16	1.200	1.16
Random errors combined						**1.24**	**1.25**	**1.16**	**1.26**	**1.29**
Power measurement	Systematic	1.00			0.05	1.05			1.050	1.05
Flow measurement		1.00			0.10		1.100	1.08	1.100	1.08
Heat transfer coefficient					0.20			1.20		1.20
System errors combined						**1.05**	**1.10**	**1.30**	**1.16**	**1.36**
Product of random and System errors						**1.30**	**1.38**	**1.50**	**1.45**	**1.75**

factors with that obtained from the systematic error sub-factors. Table III presents the EHCFs provided by PLTEMP/ANL[2]. As shown in Table III, the statistical method is applied to random errors, while the multiplicative method is applied to systematic errors.

2.2 Method for Predicting OPAL HCF

In this study, it is assumed that OPAL employs the 3-factors EHCF ($F_{q''}$, F_b, F_f) that is applied to PLTEMP/ANL, and predictions are performed accordingly. $F_{q''}$ is the hot channel factor caused by the fuel surface heat flux rise, F_b is the factor caused by the coolant temperature rise, and F_f is the factor caused by the film temperature rise. The equations used for the calculation are as follows.

$$T_{out,int} - T_{in} = (T_{out,avg} - T_{in}) \times F_r \quad (3)$$

$$T_{out,hot} = T_{in} + (T_{out,int} - T_{in}) \times F_b \quad (4)$$

$$MDNBR = \frac{\mathrm{MDNBR_{int}}}{F_{q''}} \quad (5)$$

$$Mirshak-Durant-Towell\ Correlation: \quad q''_{CHF}=1.51(1+0.1198U)(1+0.00914\Delta T_{sub})\cdot(1+0.19P)\cdot 1000 \tag{6}$$

$$T_{fc,hot}=T_{wc,hot}+\left(T_{fc,int}-T_{wc,int}\right)\times F_{q''} \tag{7}$$

$$T_{fc,int}=T_{bulk,int}+\frac{q''_{avg}\cdot PPF}{h}+\frac{q''_{avg}\cdot PPF\cdot t_{oxide}}{k_{oxide}}+\frac{q''\cdot PPF\cdot t_{clad}}{k_{clad}}+\frac{q''\cdot PPF\cdot t_{meat}}{4\cdot k_{meat}} \tag{8}$$

$$Dittus-Boelter\ Correlation: \quad Nu=0.023Re^{0.8}Pr^{0.4} \tag{9}$$

$$T_{wall,hot}=T_{bulk,hot}+\left(T_{wall,int}-T_{bulk,int}\right)\times F_f \tag{10}$$

where int(intermediate channel) is the channel considering of power peaking factors without multiplication of engineering hot channel factors($F_{q''}$, F_b, F_f), fc is the fuel center, and wc is the wall center.

In the calculation, the power distribution of OPAL is applied[4], and it is assumed that the flow velocity of the hot channel is identical to that of the average channel.

Table 4 summarizes the parameters of OPAL used in the calculation. All OPAL parameters used in the calculation were obtained from the IAEA database and OPAL-related documents[4,7,8].

Table IV: OPAL design parameters

Parameter	Value
PPF	3
Total power	18.8MW
Number of plate per assembly	21
Number of assembly	16
q''_{avg}*	660kW/m^2
Channel width	70.5mm
Channel thickness	2.45mm
Meat width	65mm
Meat length	615mm
Meat thickness	0.61mm
Meat thermal conductivity	33.6W/(mK)
Cladding thickness	0.37mm
Cladding thermal conductivity	180W/(mK)
Oxide layer thickness	50μm
Oxide layer thermal conductivity	2.25W/(mK)
Channel average velocity	8.6m/s
Inlet temperature	36℃
Average channel outlet temperature	45.6℃
Intermediate channel outlet temperature	60.9℃
Average channel maximum wall temperature	60.4℃
Intermediate channel maximum wall temperature	98.4℃
Minimum saturation temperature	118℃
Inlet pressure	3.7bar
Outlet pressure	1.864bar
MDNBR	2.58
Fuel temperature limit**	200℃

* 18.8MW divided by the total heat transfer area, yields a value of 700kW/m^2. In this study, the heat flux of 660kW/m^2 used for the EHCF evaluation was calculated through a heat balance to satisfy the inlet-outlet temperature of the average channel presented in the OPAL SAR.
** It is mentioned in the OPAL SAR that the maximum temperature at the center of the meat is below 200℃ for normal operation conditions.

2.3 Results of OPAL HCF Prediction and Evaluation

Using Eq. (3) and Table IV, F_r is calculated. Since the value of PPF is 3, F_z can be obtained by dividing the PPF by F_r, yielding a value of 1.079.

The value of F_b was assumed to be 1.24[8]. Since F_b does not have a significant effect on the wall temperature, it shows little variation. Fig. 1. illustrates the variation of F_f under OPAL's normal operation conditions, satisfying the maximum fuel temperature of 200℃. Using Eq. (4) and with the value of F_b, $T_{out,hot}$ was calculated to be 66.636℃

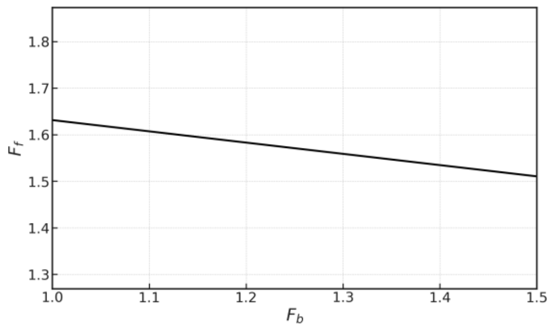

Fig. 1. variation of F_f under OPAL's normal operation conditions, satisfying the maximum fuel temperature of 200℃.

Using Eq. (5) and Table IV, $F_{q''}$ is calculated. $MDNBR_{int}$ was determined as the ratio of q''_{CHF} to q''_{max}, where q''_{max} calculated to be 1980kW/m^2, by multiplying q''_{avg} by the PPF. By applying the channel average velocity, temperature difference between minimum saturation temperature and inlet temperature, and pressure of channel center to Eq. (6), q''_{CHF} was calculated to be 6318.1kW/m^2. With the value of q''_{CHF} and q''_{max}, $MDNBR_{int}$ was calculated to be 3.191. Therefore, the value of $F_{q''}$ is 1.237.

Using Eq. (10) and Table IV, F_f is calculated. $T_{bulk,hot}$ was calculated to be 51.818℃ by the average of $T_{out,hot}$ and T_{in}, and $T_{bulk,int}$ was calculated to be 48.95℃ by the average of $T_{out,int}$ and T_{in}. Using Eq. (7) and Table IV, $T_{wc,hot}$ is calculated. The value of $T_{fc,hot}$ is assumed as 200℃, which represents the maximum fuel temperature limit. Using Eq. (8) and Table IV, $T_{fc,int}$ is calculated. The heat transfer coefficient used in Eq. (8) was calculated using Eq. (9), the Dittus-Boelter correlation with the water properties evaluated at $T_{bulk,int}$=48.95 ℃ , $P_{bulk,int}$=2.782bar. With the value of $T_{wc,int}$ and $F_{q''}$, $T_{wc,hot}$

was calculated to be 129.6℃. Therefore the value of F_f is 1.574 and it is the maximum value satisfying the fuel temperature limit of 200℃. Table V summarizes the evaluation results.

Table V: Evaluation results of peaking factors and OPAL HCFs

Parameter	Value
F_r	2.779
F_z	1.079
F_b	1.240
F_f	≤1.574
$F_{q''}$	1.237

3. Conclusions

In this study, the HCFs and uncertainty factors of various plate type fueled research reactors were investigated, and a method for evaluating HCFs through the application of uncertainty factors was presented. Furthermore, OPAL, for which the HCF has not been publicly disclosed, was selected as a reference reactor to predict its HCF. Predicting the unknown HCF of OPAL provides an advantage for optimizing thermal-hydraulic design.

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