Effect of Hot Channel Factors and Flow Velocity on ONB Temperature Margin

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1. Introduction

For the safe operation of a nuclear reactor the heat generated in the core during normal operation must be removed reliably by the coolant. In research reactors thermal-hydraulic behavior is analyzed and evaluated during the design stage to confirm that the coolant has sufficient heat removal capability under normal operating conditions. The safety margin to the ONB (Onset of Nucleate Boiling) is one of the measures in core thermal-hydraulic design that is applied differently depending on the reactor design [1].

The ONB is defined as the point where vapor bubbles first appear on the heated surface of the coolant. After the ONB, boiling continues to grow and reaches the DNB (Departure from Nucleate Boiling). Beyond the DNB, the coolant can no longer remove heat effectively and a critical event may follow. Since the DNB is always preceded by the ONB, the ONB occurrence is considered a conservative criterion for design. Moreover, once the ONB is exceeded, boiling inside the coolant channel increases and the flow becomes unstable, which may lead to premature burnout. Therefore, evaluation of the ONB margin is often considered in core thermal–hydraulic design to establish safe normal operating conditions.

Different research reactors adopt different approaches to ONB. The OPAL (Open Pool type Australian Light-water) reactor adopts the ONB as a steady-state non-safety-relevant design basis and is designed to maintain a margin to the ONB heat flux [2]. In contrast domestic research reactors adopt the ONB temperature margin during steady-state operation as a design basis [3].

For conservative evaluation of core thermal–hydraulic design, the most unfavorable hot channel conditions are assumed. Hot channel condition is established by multiplying the HCFs to the channel under heat flux conditions assuming power peaking. Among the HCFs, F_b and F_f will be considered, where F_b is the bulk temperature rise hot channel factor and F_f is the film temperature rise hot channel factor. In this study the minimum ΔT_{ONB} was calculated for the hot channel of a research reactor using plate-type fuel. The variation of the ONB margin with coolant velocity and HCFs (F_b, F_f) was then investigated.

2. Methods and Results

2.1 ONB & wall Temperatures calculation conditions

The calculation was based on the design of a 20 MWt research reactor with plate-type fuel. The inlet temperature of the coolant channel was set to 36 °C and the inlet pressure was set to 3.5 bar. The geometry of the fuel was assumed to follow that of the JRTR (Jordan Research and Training Reactor) fuel, which is designed by KAERI (Korea Atomic Energy Research Institute) [4]. The fuel consists of 16 assemblies each containing 21 fuel plates and has $750\ \mathrm{kW/m^2}$ average heat flux.

For the hot channel calculation, a power peaking factor of 3 was applied, with an axial peaking factor of 1.2 represented by a cosine function center peak. The reduction in coolant velocity within the hot channel was not considered, since it was assumed to be included in the film temperature rise hot channel factor.

2.2 Calculation methods of ONB Temperature and Wall Temperature and the effects of influencing factors

The procedure for calculating the wall temperature in the hot channel is shown in Eq. (1) to Eq. (4).

$$Q = \dot{m}c_p(T_b - T_{in}) \tag{1}$$

$$q'' = h(T_w - T_b) \tag{2}$$

$$T_{b,hot} = T_{in} + \left(T_{b,radial\ peak} - T_{in}\right) \cdot F_b \tag{3}$$

$$T_{w,hot} = T_{b,hot} + \left(T_{w,radial\ peak} - T_{b,radial\ peak}\right) \cdot F_f \tag{4}$$

Through this calculation, the effects of F_b, F_f, and v, which are the focus of this study, can be identified. F_b is multiplied by the enthalpy rise in the hot channel and is therefore proportional to the bulk temperature. F_f is multiplied by the temperature difference between the wall and the bulk in the radial peaking channel, and is therefore proportional to the hot channel wall temperature.

The heat transfer coefficient is obtained using the Dittus-Boelter correlation, as shown in Eq (5). Since the correlation is proportional to the Reynolds number to the power of 0.8, an increase in flow velocity leads to an increase in heat transfer coefficient, which lowers the wall temperature. Consequently, the hot channel wall temperature, $T_{w,hot}$, decreases.

$$Nu = 0.023Re^{0.8}\,Pr^{0.4} = \frac{hD_h}{k} \tag{5}$$

The ONB temperature is calculated using the Bergles-Rohsenow correlation in Eq (6) and Eq (7). The ONB temperature obtained at 10 nodes is compared with the hot channel wall temperature, $T_{w,hot}$, to determine the location with the minimum ONB margin.

$$T_{ONB} = T_{sat} + \frac{5}{9} \cdot \left(\frac{9.23q''_{ONB}}{10^4 P^{1.156}}\right)^{\frac{P^{0.0234}}{2.16}} \tag{6}$$

$$T_{ONB} = T_{b,hot} + \frac{q''_{ONB}}{h} \tag{7}$$

Nomenclature	
Q	Power
$\dot{m}$	Mass flow rate
c_p	Constant pressure specific heat
q''	Heat flux
q''_{ONB}	ONB heat flux
h	Heat transfer coefficient
P	Pressure
T_{in}	Coolant inlet temperature
T_w	Wall temperature
T_b	Coolant bulk temperature
$T_{b,radial\ peak}$	Coolant bulk temperature in the radial peaking channel
$T_{w,radial\ peak}$	Wall temperature in the radial peaking channel
$T_{b,hot}$	Coolant bulk temperature in the hot channel
$T_{w,hot}$	Wall temperature in the hot channel
T_{ONB}	ONB temperature
T_{sat}	Saturation temperature

The values of F_b and F_f differ depending on the research reactor designs [5] - [8]. As the OPAL HCF values are not publicly available, it was predicted based on the methodology presented in the study [8]. As the study provides a range of HCF values for film temperature rise, the maximum F_f value is adopted in this study.

Table I: Research reactor hot channel factors

	F_b	F_f
JRR-3	1.32	1.36
MURR-LEU	1.54	1.46
PLTEMP/ANL	1.45	1.75
OPAL	1.24	1.57*

*The maximum value of F_f within the predicted range

Table I shows the F_b and F_f values used in the study. Based on the data in Table 1, the ranges of F_b and F_f were set to 1.1-1.8.

Table II summarizes the ranges of the major parameters. The coolant velocity range was set to 5-11 m/s, while the OPAL research reactor, a 20 MW facility, which has a velocity of 8.2 m/s [2].

Table II: Parameter ranges

Parameters	Ranges
F_b	1.1 - 1.8
F_f	1.1 - 1.8
v	5 - 11 m/s

2.3 Calculation results of ONB temperature and wall temperature

Figure 2a and 2b show the ONB temperature margin as a function of the bulk temperature rise hot channel factor and the film temperature rise hot channel factor at a coolant velocity of 8 m/s and 10 m/s, respectively. As F_b and F_f increase, the ONB temperature margin decreases. It is observed that F_f reduces the margin more significantly than F_b. The margin also decreases considerably when the coolant velocity is reduced.

Figure 3a and Figure 3b summarize the node number where the minimum ONB temperature margin occurs at coolant velocities of 8 m/s and 10 m/s, respectively. Node 1 corresponds to the upstream, with higher node numbers indicating positions farther downstream as shown in Figure 1. In most cases, the minimum ONB margin was found near the center of the channel. Meanwhile, in some regions, the minimum ONB margin was observed near the downstream.

When F_b is large and F_f is small, the minimum ONB margin appears at a higher location. According to Eq (3), F_b is multiplied by the coolant enthalpy rise and thus a larger F_b results in a greater bulk temperature rise in the hot channel. According to Eq (4), F_f is multiplied by the temperature difference between the wall and the bulk, so a larger F_f increases the influence of this temperature difference. Therefore, in the region where F_b is large and

F_f is small, the effect of the bulk temperature difference between the inlet and outlet of the hot channel becomes dominant while the effect of the wall and bulk temperature difference is reduced. Consequently, the influence of the higher bulk temperature near the outlet increases and the minimum ONB margin shifts to a location farther downstream.

Figure 4 shows the wall temperature, ONB temperature, and minimum ONB temperature margin in hot channel for F_b = 1.45 and F_f = 1.75. When the coolant velocity exceeds 9.77 m/s, the ONB temperature becomes higher than the wall temperature, yielding a positive margin.

Table 3 presents the flow velocity at which the wall temperature coincides with the ONB temperature for the F_b and F_f values in Table 1. As the F_b and F_f values increase, a higher flow velocity is obtained.

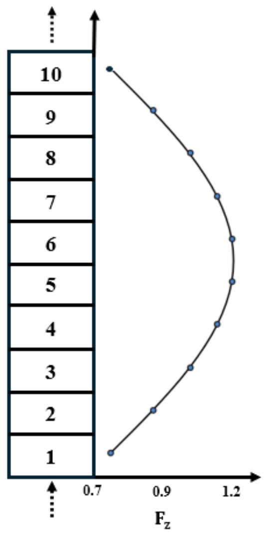

Fig. 1. Axial distribution along the channel

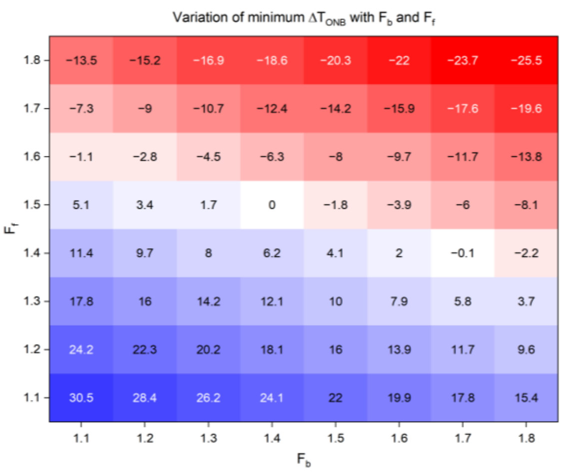

Fig. 2a. Variation of the ONB margin with bulk temperature rise and film temperature rise HCF (v=8m/s).

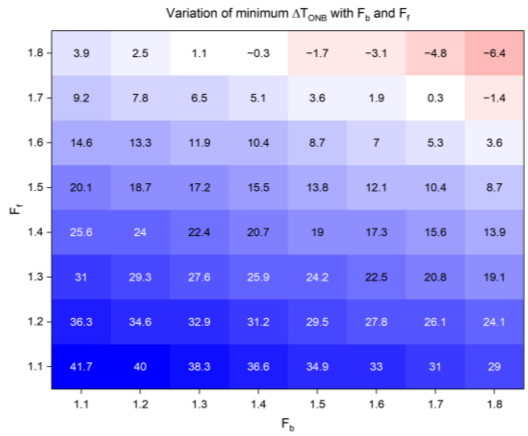

Fig. 2b. Variation of the ONB margin with bulk temperature rise and film temperature rise HCF (v=10m/s).

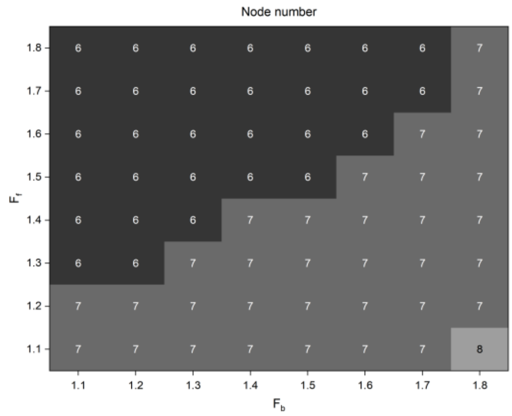

Fig. 3a. Minimum ONB temperature margin location (v=8m/s).

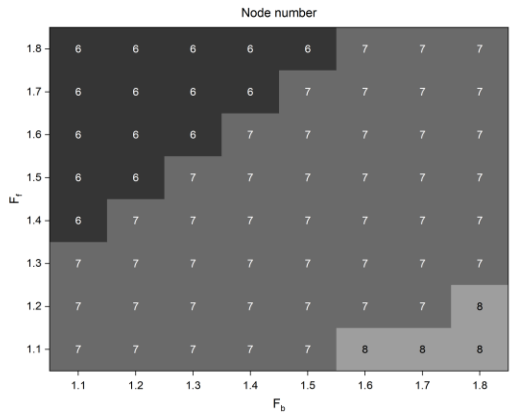

Fig. 3b. Minimum ONB temperature margin location (v=10m/s).

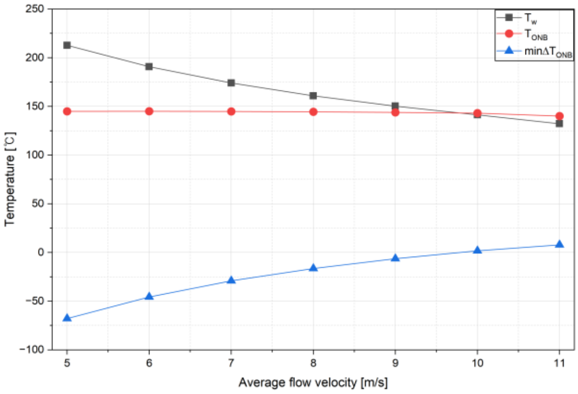

Fig. 4. Temperature variations and ONB temperature margin with coolant velocity (F_b=1.45, F_f=1.75).

Table III: Velocities at ONB condition

	$T_w(= T_{ONB})$ [℃]	v [m/s]
JRR-3	146.6	7.02
MURR-LEU	144.3	8.03
PLTEMP/ANL	143.3	9.77
OPAL	145.3	8.17

3. Conclusions

In this study the effects of key parameters on the ONB margin in the hot channel of a research reactor were evaluated. An increase in F_b (bulk temperature rise hot channel factor) and F_f (film temperature rise hot channel factor) reduced the ONB temperature margin, with F_f having a stronger influence than F_b. Furthermore, these factors also affected the location at which the minimum ONB temperature margin occurred. In the range where F_b has large values and F_f has small values, the minimum ONB margin appeared farther downstream due to the influence of the increased outlet temperature.

The coolant velocity was found to increase the heat transfer coefficient, which lowered the wall temperature and thereby increased the ONB margin. This evaluation provides a basis for determining the appropriate range of coolant velocities for steady-state operation.

Moreover, HCFs can be applied in different ways depending on the calculation method. Although the specific results may vary with the methodology, analyzing the trends with respect to parameter values is meaningful for identifying how and to what extent these factors affect the temperature evaluation in the hot channel.

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