CHF Correlation Scheme Proposed for Research Reactors using Plate-Type Fuel
- New CHF Correlation under CCFL Condition -

IGORR-IV

Masanori Kaminaga
Yukio SUDO
Tsuneo KODAIRA
Nobuaki OHNISHI

Department of Research Reactor
Japan Atomic Energy Research Institute (JAERI)

Presented at IGORR-IV, Gatlinburg, TN
May 25, 1995
Introduction

- The detailed understanding of Critical Heat Flux (CHF) for vertical rectangular channels is essential for core thermal-hydraulic design and safety analysis of research reactors using plate-type fuel.
- In research reactors which are cooled by downward core flow, the core flow reversal should take into account for design and safety.
- At JAERI, reduced enrichment work for JRR-4 is now in progress. JRR-4 is a swimming pool type research reactor with the maximum power of 3.5 MWt. Because of comparatively small thermal power, it is not necessary to credit auxiliary or emergency pumps for the decay heat removal after coast-down of main pumps in case of emergency. Therefore, the core flow reversal would occur just after coast-down of main pumps.
- High power research reactors have auxiliary or emergency pumps for the decay heat removal after coast-down of main pumps in case of operational transients or accident condition such as "loss of commercial electric power supply". So that the core flow reversal could occur under decay heat level low enough and safety margin against CHF is large enough.
Objective of this study

For the low mass flux region including stagnant flow condition, CHF is closely related to *Counter-Current Flow Limitation* (CCFL). The CHF correlation in this region used so far at JAERI is very conservative one, that is,

» The effects of channel inlet subcooling and axial heat flux distribution on CHF in this region have not been taken into account.

Therefore, the effects of channel inlet subcooling and axial heat flux distribution on CHF were investigated in this study based on the existing CHF experimental data under low mass flux region.

The CHF at high subcooling and high mass flux were also investigated to the experimental data at flow excursion (FE) as well as CHF.
Previous CHF Correlation Scheme Proposed for Research Reactors using Plate-Type Fuel

\[ q_{CHF,1} = 0.005 |G^*|^{0.611} \]  

(1)

\[ q_{CHF,2} = \frac{A}{A_H} \Delta T_{SUB,in}^* |G^*| \]  

(2)

\[ q_{CHF,3} = 0.7 \frac{A}{A_H} \frac{\sqrt{W/\lambda}}{\left\{1 + (\rho_g/\rho_\ell)^{1/4}\right\}^2} \]  

(3)

\[ q_{CHF,4} = 0.005 |G^*|^{0.611} \left(1 + \frac{5000}{|G^*|} \Delta T_{SUB,O}^* \right) \]  

(4)

\[ q_{CHF,A} = 0.005 |G^*|^{0.611} \left(1 + \frac{5000}{|G^*|} \Delta T_{SUB,in}^* \right) \]  

(4')

The diagram illustrates the CHF correlation scheme with regions for low, medium, and high mass flux. Each region is defined by different correlations depending on the mass flux and temperature difference conditions. The equations are used to calculate the critical heat flux \( q_{CHF} \) for both upflow and downflow conditions.
Experimental conditions of existing CHF tests investigated in this study

- **IGORR-IV**

  - **Coolant:** Water
  - **Pressure:** Atmospheric pressure
  - **Mass flux:** 0 to -73 kg/m²sec (Downward) (0: stagnant flow conditions)
  - **Inlet subcooling:** 0 to 78 K
  - **De:** 4.3 to 9.1 (mm)
  - **L/De:** 71 to 174 (-)
  - **Axial heat flux distribution:** Non-uniform and Uniform
  - **Axial peaking factor:** 1.0 to 1.6 (-)
  - **Total number of data:** 69
Axial heat flux distribution of existing CHF tests investigated in this study
Comparison between all JAERI experimental results and previous CHF correlation under CCFL condition for rectangular channels

IGORR-IV

CHF experimental results for both non-uniform and uniform heat flux condition

- $\Delta T_{sub,in} = 27-68^\circ \text{C}$ U, Gap=2.25mm, L=750mm
- $\Delta T_{sub,in} = 28-59^\circ \text{C}$ U, Gap=2.8mm, L=375mm
- $\Delta T_{sub,in} = 1-58^\circ \text{C}$ U, Gap=5.0mm, L=750mm
- $\Delta T_{sub,in} = 11-77^\circ \text{C}$ N/U Case 1
- $\Delta T_{sub,in} = 2-78^\circ \text{C}$ N/U Case 2, Gap=2.25mm, L=750mm
- $\Delta T_{sub,in} = 0-74^\circ \text{C}$ N/U Case 3

+33%
-33%

U : Uniform heat flux
N/U : Non-uniform heat flux

$\ddagger$ DNB data obtained under stagnant flow (zero flow) condition

$q^*_{CHF,3} = 0.7 \frac{A}{A_H} \frac{\sqrt{W/\lambda}}{\left\{1 + \left(\rho_f/\rho\right)^{1/4}\right\}^2}$
Comparison between experimental results and previous CHF correlation under CCFL condition for rectangular channels, $\Delta T_{SUB,in} > 30$

(Except the data obtained saturated or near saturated condition at the inlet of channel)

IGORR-IV

CHF experimental results for both non-uniform and uniform heat flux condition

$\Delta T_{sub,in} =$ 30-68 °C U  Gap=2.25mm, L=750mm
$\Delta T_{sub,in} =$ 57-59 °C U  Gap=2.8mm, L=375mm
$\Delta T_{sub,in} =$ 41-58 °C U  Gap=5.0mm, L=750mm
$\Delta T_{sub,in} =$ 36-77 °C N/U Case 1
$\Delta T_{sub,in} =$ 36-78 °C N/U Case 2  Gap=2.25mm, L=750mm
$\Delta T_{sub,in} =$ 70-74 °C N/U Case 3

+33%  -33%

U : Uniform heat flux
N/U: Non-uniform heat flux
■ DNB data obtained under stagnant flow (zero flow) condition

$\dot{q}^*_{CHF,3} = 0.7 \frac{A}{A_H} \frac{\sqrt{W / \lambda}}{\left[1 + \left(\rho_g / \rho_f\right)^{1/4}\right]^2}$

$q^*_{CHF,3}$ (Calculated CHF) (-)
Based on the investigation results of this study, following correlation is proposed as a preliminary CHF correlation under CCFL condition to take into account the channel inlet subcooling effects to CHF.

\[
q_{CHF,3NEW}^* = 0.7 \frac{A}{A_H} \frac{\sqrt{\dot{W}/\lambda}}{\left\{1 + \left(\frac{\rho_g}{\rho_\ell}\right)^{1/4}\right\}^2 \left\{1 + \Delta T_{SUB,in}^*\right\}} (5)
\]

\[
\Delta T_{SUB,in}^* = \frac{C_{pl} \Delta T_{SUB,in}}{h_{fg}}
\]
Comparison between all JAERI experimental results and New CHF correlation under CCFL condition for rectangular channels

IGORR-IV

CHF experimental results for both non-uniform and uniform heat flux condition

\[ q^*_{CHF,NEW} = 0.7 \frac{A}{A_H} \frac{\sqrt{W/\lambda}}{\left\{1 + \left(\frac{\rho_g}{\rho_f}\right)^{1/4}\right\}^{1/2}} \left\{1 + \Delta T_{SUB,in}^*\right\} \]

- \( \Delta T_{SUB,in} = 27-68^\circ C \) U Gap=2.25mm, L=750mm
- \( \Delta T_{SUB,in} = 28-59^\circ C \) U Gap=2.8mm, L=375mm
- \( \Delta T_{SUB,in} = 1-58^\circ C \) U Gap=5.0mm, L=750mm
- \( \Delta T_{SUB,in} = 11-77^\circ C \) N/U Case 1 Gap=2.25mm, L=750mm
- \( \Delta T_{SUB,in} = 2-78^\circ C \) N/U Case 2 L=750mm
- \( \Delta T_{SUB,in} = 0-74^\circ C \) N/U Case 3

U: Uniform heat flux
N/U: Non-uniform heat flux

- DNB data obtained under stagnant flow (zero flow) condition
- +33%
- -33%
Effect of axial heat flux distribution to CHF

Effects of Axial Peaking Factor on CHF, Gap=2.25mm, L=750mm

$q_{CHF,measured}/q_{CHF,NEW} = 0.7 \frac{A}{A_H} \frac{\sqrt{W/\lambda}}{\left[1 + \left(\rho_s/\rho_f\right)^{1/4}\right]^2} \left[1 + \Delta T_{SUB,IN}^*\right]$

Peaking Factor $f_i (q_{max}/q_{av})$ (-)
Experimental conditions of Flow Excursion (FE) and CHF test performed at ORNL
High mass flux region

- Coolant: Water
- Inlet coolant temperature: 45 °C
- Exit coolant pressure: 1.7 MPa
- Nominal average heat flux range: 6~14 MW/m²
- Corresponding velocity range: 8~21 m/s
- Channel configuration: Rectangular channel, 1.27 x 12.7 x 507 mm
Comparison between measured FE heat flux, CHF obtained at ORNL and CHF predicted by Eq. (4)

\[ q_{CHF} \text{ predicted by Eq.}(4) \quad (\text{MW/m}^2) = 0.005 C_T^{0.611} \left( 1 + \frac{5000}{G^{*}} \Delta T_{SUB,O}^{*} \right) \] (4)
New CHF Correlation Scheme Proposed for Research Reactors using Plate-Type Fuel

\[ q_{CHF,4}^* = 0.005 |G^*|^{0.611} \left( 1 + \frac{5000}{|G^*|} \Delta T_{SUB,O}^* \right) \]  
\[ q_{CHF,1}^* = 0.005 |G^*|^{0.611} \]  
\[ q_{CHF,2}^* = \frac{A}{A_H} \Delta T_{SUB,in}^* |G^*| \]  
\[ q_{CHF,3}^* = 0.7 \frac{A}{A_H} \frac{\sqrt{W/\lambda}}{\left(1 + (\rho_g / \rho_\ell)^{1/4}\right)^2} \left\{1 + \Delta T_{SUB,in}^*\right\} \]
Region boundaries are identified by the following equations.

\[
G_1^* = \left[ \frac{0.005}{A} \frac{\Delta T_{SUB,in}}{A_H} \right] \left[ \frac{1}{0.389} \right]
\]

\[
G_2^* = \left[ 140 \frac{A}{A_H} \frac{\sqrt{W/\lambda}}{\left\{1 + \left(\frac{\rho_g}{\rho_\ell}\right)^{1/4}\right\}^{1/2}} \left\{1 + \Delta T_{SUB,in}^*\right\} \right] \left[ \frac{1}{0.611} \right]
\]

\[
G_3^* = 0.7 \left\{1 + \left(\frac{\rho_g}{\rho_\ell}\right)^{1/4}\right\} \left\{1 + \frac{1}{\Delta T_{SUB,in}^*}\right\}
\]
Factors effective to CHF in each region

<table>
<thead>
<tr>
<th>Region</th>
<th>Effective factors to CHF</th>
<th>$q^*_{CHF}$</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region I</td>
<td>$\Delta T^<em>_{SUB,O}$ and $G^</em>$</td>
<td>Eq.(4)</td>
<td>High mass flux, Upflow and Downflow</td>
</tr>
<tr>
<td>Region II</td>
<td>$G^*$</td>
<td>Eq.(1)</td>
<td>Medium mass flux, Upflow</td>
</tr>
<tr>
<td>Region II’</td>
<td>$\Delta T^<em>_{SUB,in}$, $G^</em>$ and $A/A_H$</td>
<td>Eq.(2)</td>
<td>Medium mass flux, Downflow</td>
</tr>
<tr>
<td>Region III</td>
<td>$A/A_H$, $W$ and $\Delta T^*_{SUB,in}$</td>
<td>Eq.(5)</td>
<td>Low mass flux, Upflow and Downflow</td>
</tr>
</tbody>
</table>
Conclusions

IGORR-IV

The effects of channel inlet subcooling and axial heat flux distribution on CHF under CCFL condition were investigated in this study.

As the results, Eq.(5) was proposed as a new CHF correlation including the effect of channel inlet subcooling.

Based on the comparison between Eq.(5) and CHF experimental data obtained non-uniform heat flux condition, this new correlation can be adopted within the range investigated in this study.

(Axial peaking factor : 1.0 ~ 1.6)

For high mass flux region, Eq.(4) was compared with FE and CHF experimental data obtained at ORNL. Eq(4) can be used to identify the thermal limit of research reactors for the condition investigated in this study.

A new CHF correlation scheme was proposed based on this study.
Comparison between experimental results and New CHF correlation under CCFL condition for rectangular channels, $\Delta T_{SUB,in} > 30$

(Except the data obtained saturated or near saturated condition at the inlet of channel)

IGORR-IV

CHF experimental results for both non-uniform and uniform heat flux condition

- $\Delta T_{SUB,in} = 30-68 \, ^\circ C$ U, Gap=2.25mm, L=750mm
- $\Delta T_{SUB,in} = 57-59 \, ^\circ C$ U, Gap=2.8mm, L=375mm
- $\Delta T_{SUB,in} = 41-58 \, ^\circ C$ U, Gap=5.0mm, L=750mm
- $\Delta T_{SUB,in} = 36-77 \, ^\circ C$ N/U Case 1, Gap=2.25mm, L=750mm
- $\Delta T_{SUB,in} = 36-78 \, ^\circ C$ N/U Case 2
- $\Delta T_{SUB,in} = 70-74 \, ^\circ C$ N/U Case 3

U : Uniform heat flux
N/U: Non-uniform heat flux
■ DNB data obtained under stagnant flow (zero flow) condition
△ flow (zero flow) condition

$$q_{*\text{CHF,NEW}} (Calculated CHF) (\cdot)$$

$$q_{*\text{CHF,NEW}} = 0.7 \frac{A}{A_H} \left[ \frac{\sqrt{W/L}}{\lambda} \right] \left\{ 1 + \left( \frac{\rho_g}{\rho_l} \right)^{1/4} \right\} \left\{ 1 + \Delta T_{\text{st, in}}^{*} \right\}$$
Comparison between measured FE heat flux (CHF) at ORNL and CHF predicted by Gambill & Weatherhead

$\gamma_{\text{CHF measured}} = \gamma_{\text{CHF predicted}}$