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

IGORR-IV

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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 dasign 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 nessesary 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 maim 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 enogh 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

$$q^*_{CHF,4} = 0.005 \left|G^*\right|^{0.611}\left(1 + \frac{5000}{\left|G^*\right|} \Delta T^*_{SUB,O}\right) \quad (4)$$

$$q^*_{CHF,4} = 0.005 \left|G^*\right|^{0.611} \frac{\left(1 + \dfrac{5000}{\left|G^*\right|} \Delta T^*_{SUB,in}\right)}{\left(1 + 25\left|G^*\right|^{-1.389}\dfrac{A}{A_H}\right)} \quad (4')$$

$$q^*_{CHF,1} = 0.005 \left|G^*\right|^{0.611} \quad (1)$$

$$q^*_{CHF,2} = \frac{A}{A_H} \Delta T^*_{SUB,in}\left|G^*\right| \quad (2)$$

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

219
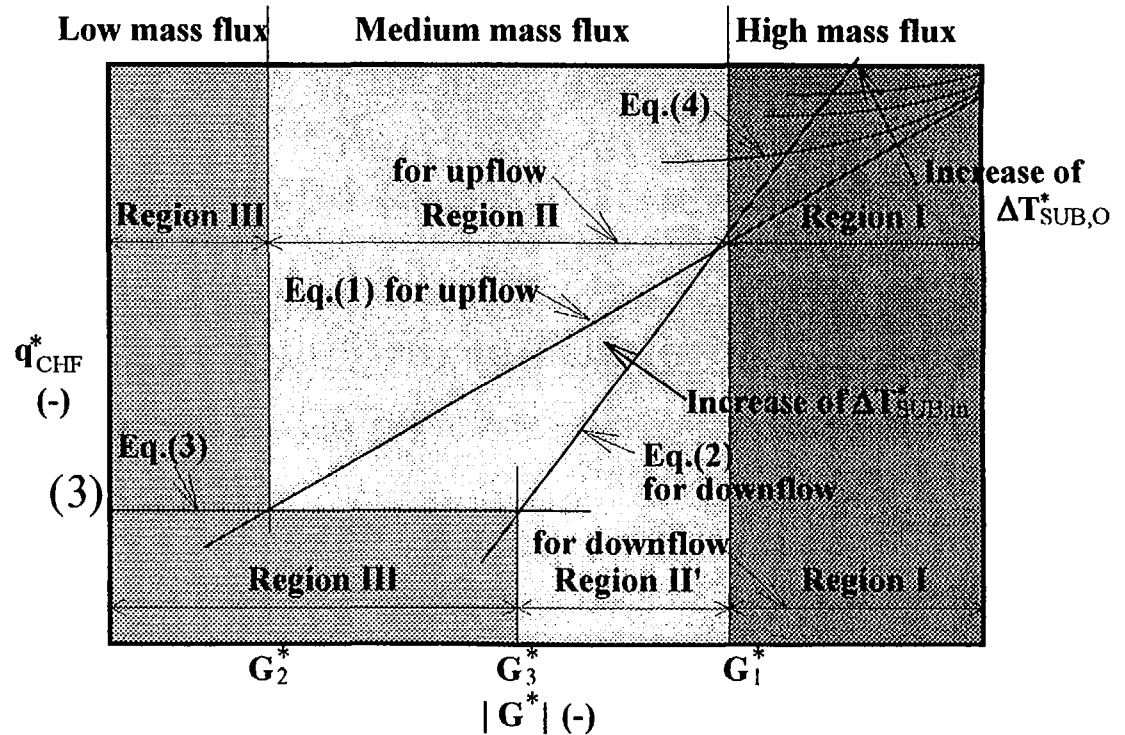
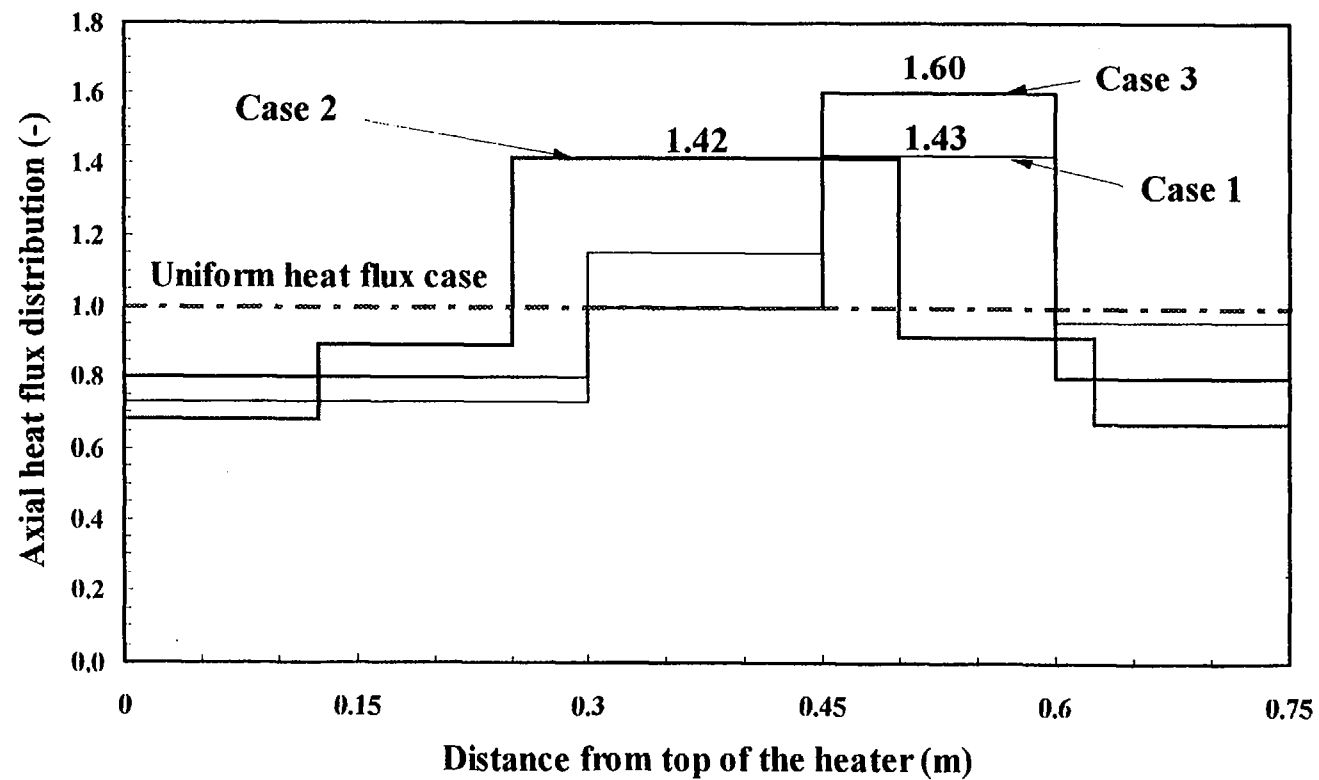# Experimental conditions of existing CHF tests investigated in this study

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- 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

220

Axial heat flux distribution of existing CHF tests investigated in this study
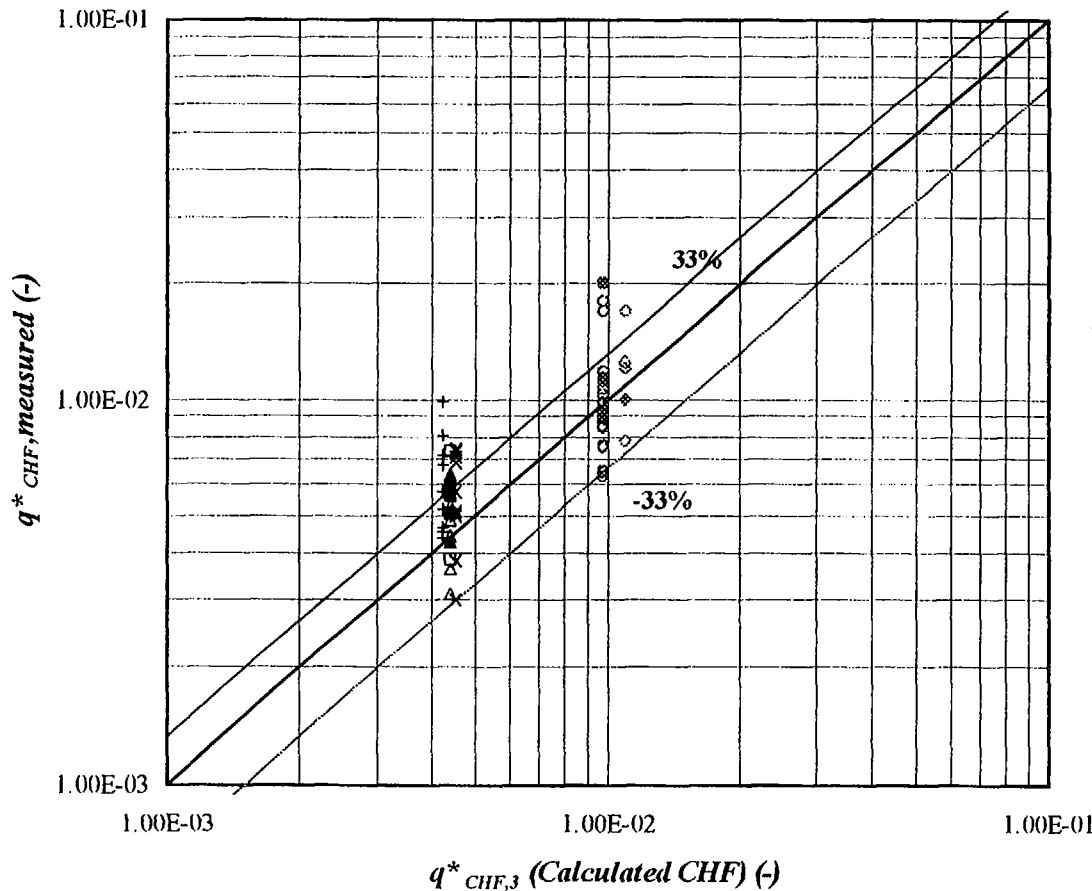
Axial heat flux distribution investigated in this study

Comparison between all JAERI experimental results and previous CHF correlation under CCFL condition for rectangular channels

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

- □ $\Delta Tsub, in$ =27-68 °C U   Gap=2.25mm, L=750mm
- ◊ $\Delta Tsub, in$ =28-59 °C U   Gap=2.8mm, L=375mm
- ○ $\Delta Tsub, in$ = 1-58 °C U   Gap=5.0mm, L=750mm
- △ $\Delta Tsub, in$ =11-77 °C N/U Case 1
- × $\Delta Tsub, in$ = 2-78 °C N/U Case 2   Gap=2.25mm, L=750mm
- + $\Delta Tsub, in$ = 0-74 °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
●

$$q^*_{CHF,3} = 0.7 \; \frac{A}{A_H} \; \frac{\sqrt{W / \lambda}}{\left\{ 1 + \left(\rho_g / \rho_l \right)^{1/4} \right\}^2}$$
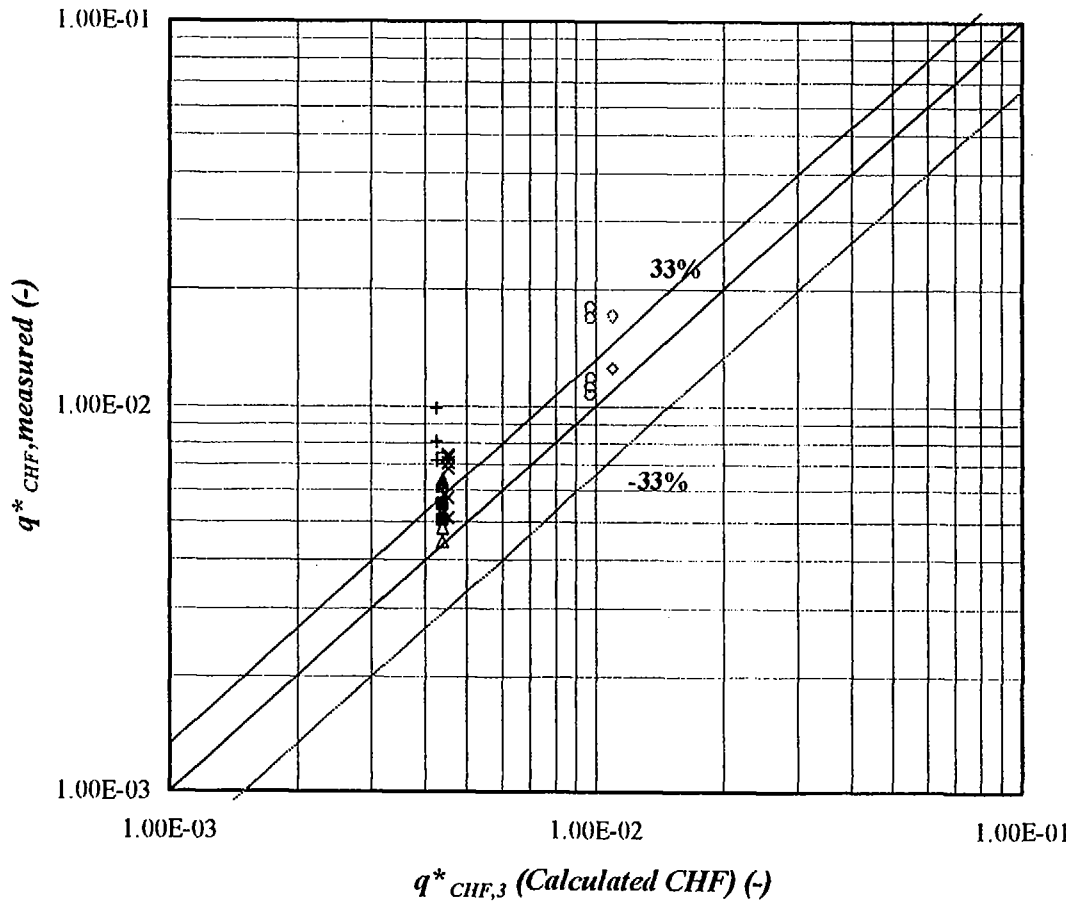
222

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)

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

q* CHF,measured (-)

1.00E-01

1.00E-02

1.00E-03

1.00E-03   1.00E-02   1.00E-01

33%

-33%

$q^*_{CHF,3}$ (Calculated CHF) (-)

□ $\Delta Tsub,in = 30\text{-}68\ °C$ U   Gap=2.25mm, L=750mm

◇ $\Delta Tsub,in = 57\text{-}59\ °C$ U   Gap=2.8mm, L=375mm

○ $\Delta Tsub,in = 41\text{-}58\ °C$ U   Gap=5.0mm, L=750mm

△ $\Delta Tsub,in = 36\text{-}77\ °C$ N/U Case 1

× $\Delta Tsub,in = 36\text{-}78\ °C$ N/U Case 2   Gap=2.25mm, L=750mm

+ $\Delta Tsub,in = 70\text{-}74\ °C$ 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

$$q^*_{CHF,3} = 0.7\ \frac{A}{A_{II}}\ \frac{\sqrt{W/\lambda}}{\left\{1+\left(\rho_g/\rho_\ell\right)^{1/4}\right\}^2}$$

New CHF correlation under CCFL condition

■ 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.

$$q^*_{CHF,3NEW} = 0.7 \ \frac{A}{A_H} \ \frac{\sqrt{W/\lambda}}{\left[1 + \left(\rho_g / \rho_\ell\right)^{1/4}\right]^2} \left\{1 + \Delta T^*_{SUB,in}\right\} \quad (5)$$
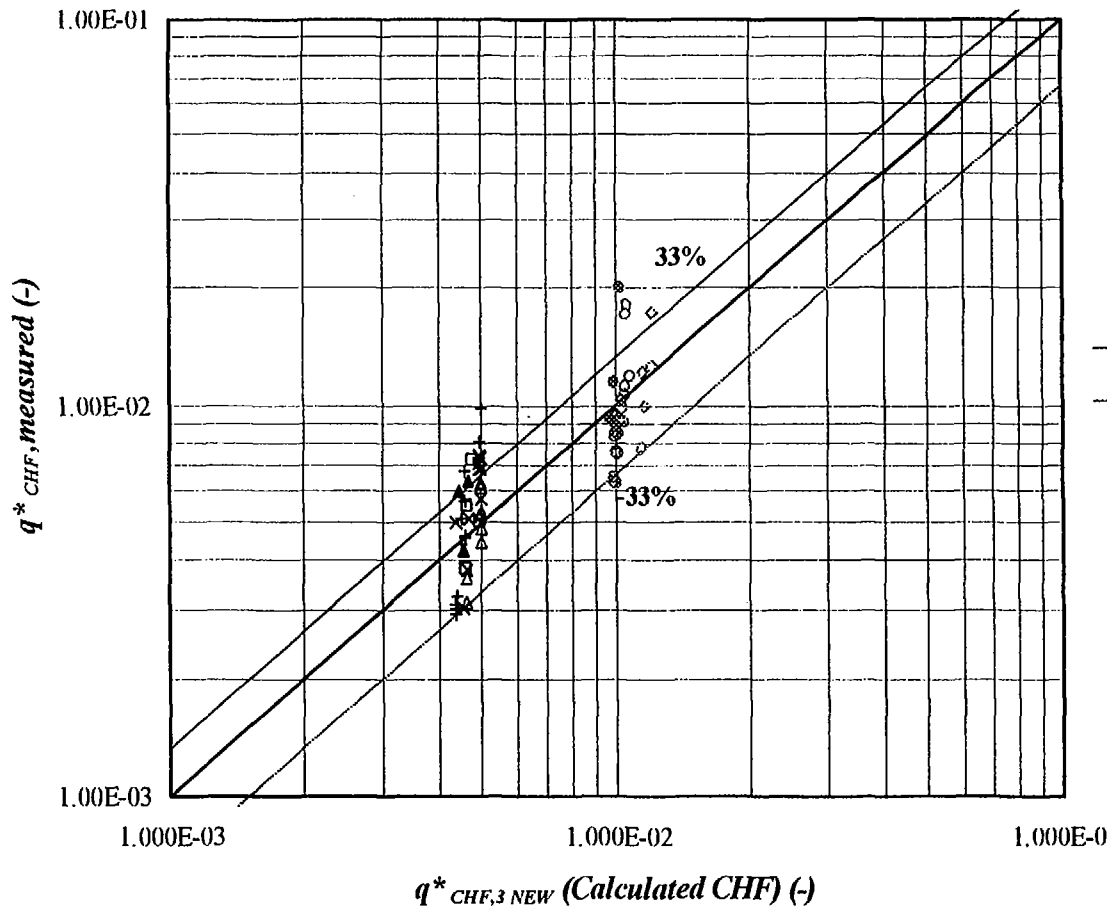
$$\Delta T^*_{SUB,in} = \frac{C_{p\ell} \Delta T_{SUB,in}}{h_{fg}}$$

Comparison between all JAERI experimental results and New CHF correlation under CCFL condition for rectangular channels

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

Legend:

□ $\Delta Tsub,in$ =27-68 °C U Gap=2.25mm, L=750mm

◇ $\Delta Tsub,in$ =28-59 °C U Gap=2.8mm, L=375mm

○ $\Delta Tsub,in$ = 1-58 °C U Gap=5.0mm, L=750mm

△ $\Delta Tsub,in$ =11-77 °C N/U Case 1

× $\Delta Tsub,in$ = 2-78 °C N/U Case 2 Gap=2.25mm, L=750mm

+ $\Delta Tsub,in$ = 0-74 °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
◉

Axis labels: $q^*_{CHF, measured}$ (-) vs $q^*_{CHF,3\,NEW}$ (Calculated CHF) (-)

$$q^*_{CHF,3NEW} = 0.7 \, \frac{A}{A_H} \, \frac{\sqrt{W/\lambda}}{\left\{1+\left(\rho_g/\rho_\ell\right)^{1/4}\right\}^2} \left\{1+\Delta T^*_{SUB,in}\right\}$$

Effect of axial heat flux distribution to CHF

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

$$q^*_{CHF,3NEW} = 0.7 \, \frac{A}{A_H} \, \frac{\sqrt{W/\lambda}}{\left\{1+\left(\rho_g/\rho_\ell\right)^{1/4}\right\}^2}\left\{1+\Delta T^*_{SUB,in}\right\}$$

226
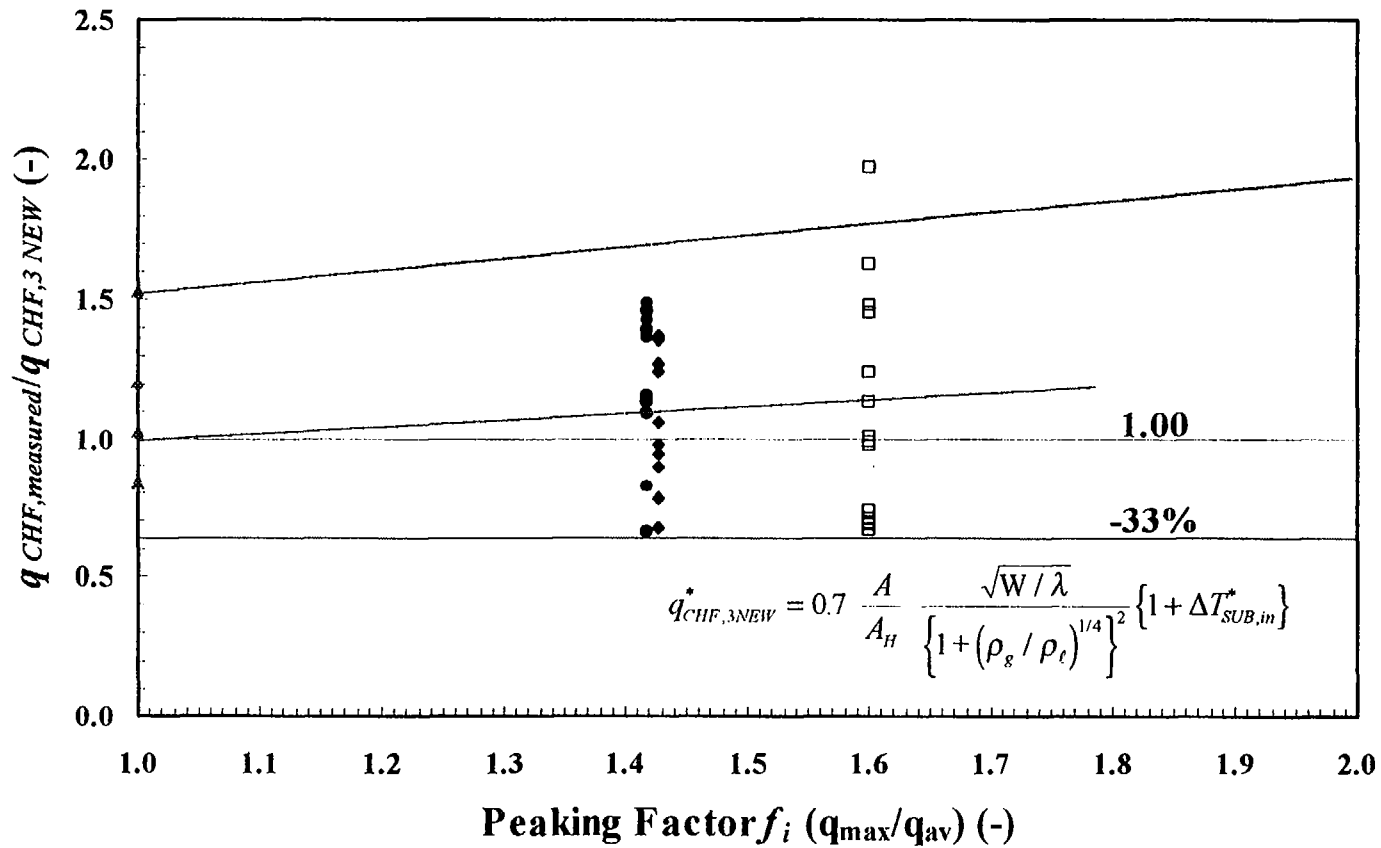
Experimental conditions of Flow Excursion (FE) and CHF test performed at ORNL

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- 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)

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TSD : Test Section Design

- ▲ TSD-3/A
- ▣ TSD-3/B
- ● TSD-3/C
- ◇ TSD-3/D
- ※ TSD-3/D True CHF
- ※ TSD-3/E
- ※ TSD-3/E True FE
- + TSD-3/F
- + TSD-3/F True FE
- ※ TSD-3/G
- ※ TSD-3/G True FE
- —— Q"CHFpredicted=Q"FEmeas
- —— +18% line
- ······ -5% line

q_{FE}(or q_{CHF})measured (MW/m²)

q_{CHF} predicted by Eq.(4) (MW/m²)
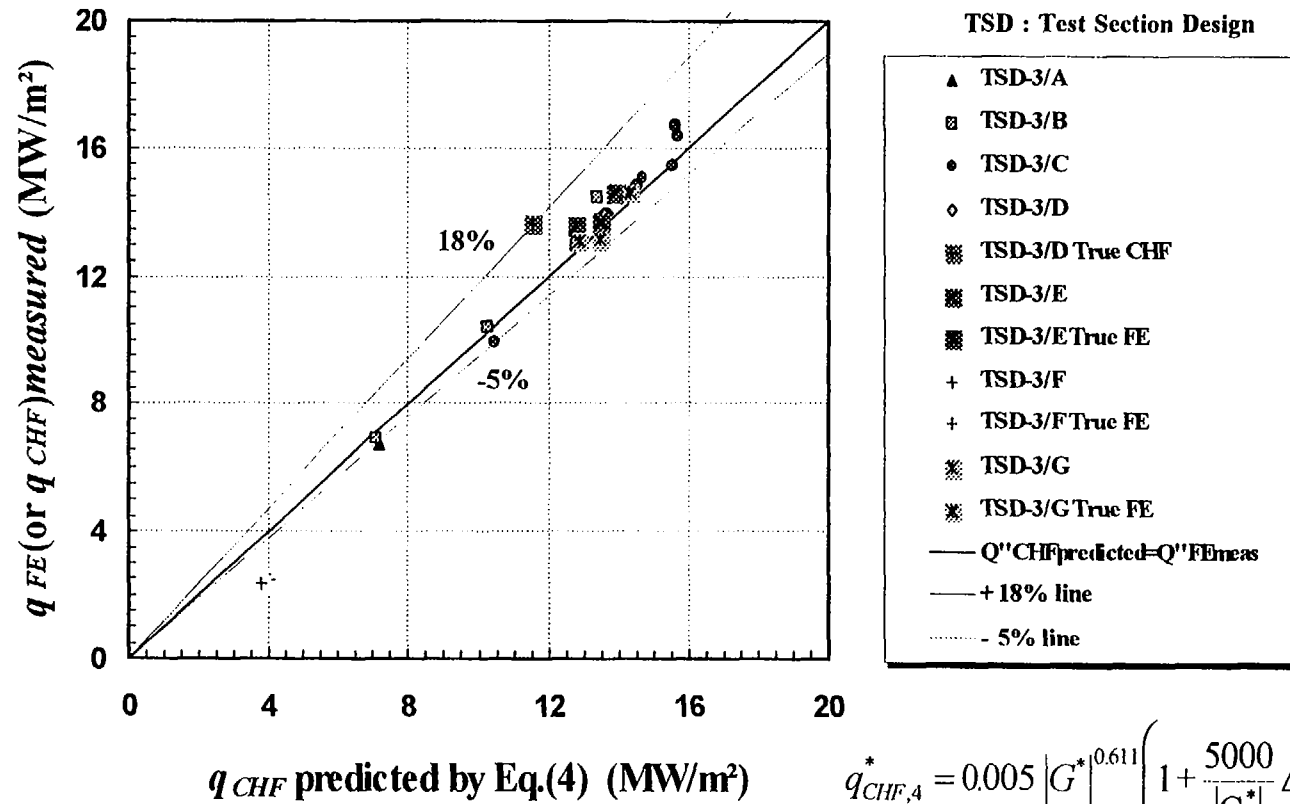
$$q^*_{CHF,4} = 0.005 \left|G^*\right|^{0.611}\left(1 + \frac{5000}{\left|G^*\right|} \Delta T^*_{SUB,O}\right) \quad (4)$$

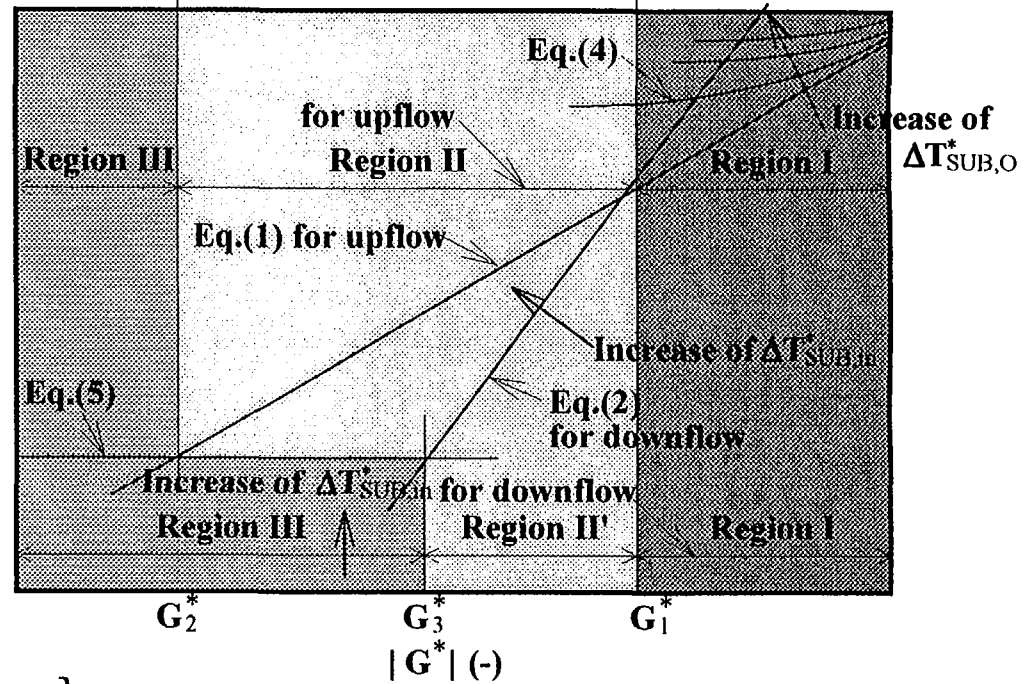# New CHF Correlation Scheme Proposed for Research Reactors using Plate-Type Fuel

$$q^*_{CHF,4} = 0.005 \, \left|G^*\right|^{0.611} \left(1 + \frac{5000}{\left|G^*\right|} \Delta T^*_{SUB,O}\right) \quad (4)$$

$$q^*_{CHF,1} = 0.005 \, \left|G^*\right|^{0.611} \quad (1)$$

$$q^*_{CHF,2} = \frac{A}{A_H} \, \Delta T^*_{SUB,in} \, \left|G^*\right| \quad (2)$$

$$q^*_{CHF,3} = 0.7 \, \frac{A}{A_H} \, \frac{\sqrt{W/\lambda}}{\left\{1 + \left(\rho_g/\rho_\ell\right)^{1/4}\right\}^2} \left\{1 + \Delta T^*_{SUB,in}\right\} \quad (5)$$

Low mass flux | Medium mass flux | High mass flux

q^*_{CHF} (-)

Eq.(4)

for upflow
Region II

Region III

Increase of $\Delta T^*_{SUB,O}$

Eq.(1) for upflow

Region I

Increase of $\Delta T^*_{SUB,in}$

Eq.(5)

Eq.(2) for downflow

Increase of $\Delta T^*_{SUB,in}$ for downflow

Region III'

Region II'

Region I'

G^*_2 G^*_3 G^*_1

$\left|G^*\right|$ (-)

Region boundaries are identified by the following equations.

230

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

(6)

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

(7)

$$G_3^* = 0.7 \frac{\sqrt{W/\lambda}}{\left\{ 1 + \left(\rho_g / \rho_\ell \right)^{1/4} \right\}^2} \left\{ 1 + \frac{1}{\Delta T_{SUB,in}^*} \right\}$$

(8)

Factors effective to CHF in each region

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Region	Effective factors to CHF	q^*_{CHF}	Note
Region I	$\Delta T^*_{SUB,O}$ and G^*	Eq.(4)	High mass flux, Upflow and Downflow
Region II	G^*	Eq.(1)	Medium mass flux, Upflow
Region II'	$\Delta T^*_{SUB,in}$, G^* and A/A_H	Eq.(2)	Medium mass flux, Downflow
Region III	A/A_H, W and $\Delta T^*_{SUB,in}$	Eq.(5)	Low mass flux, Upflow and Downflow

231

Conclusions

- 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.
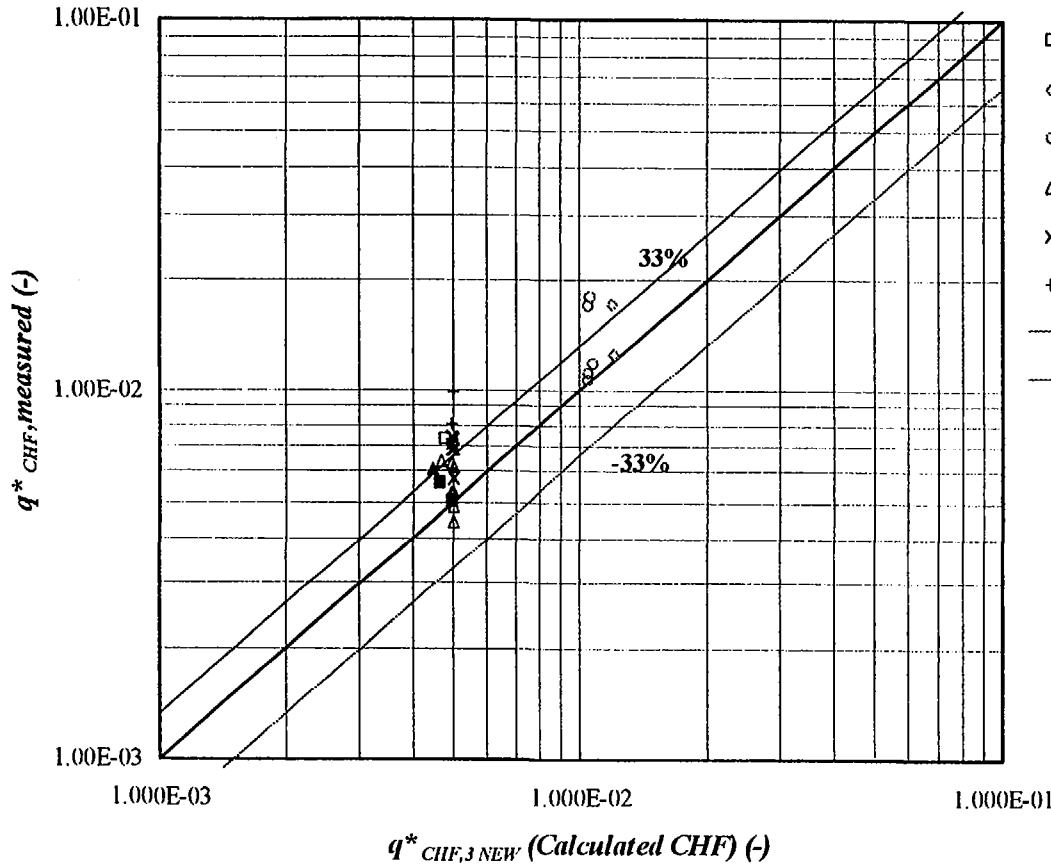
  (Axial peaking factor : 1.0 ~ 1.6)

- 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)

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

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△	$\Delta Tsub, in = 36\text{-}77$ °C N/U Case 1
×	$\Delta Tsub, in = 36\text{-}78$ °C N/U Case 2 Gap=2.25mm, L=750mm
+	$\Delta Tsub, in = 70\text{-}74$ °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
◉

Graph axes: $q^*_{CHF, measured}$ (-) versus $q^*_{CHF,3 NEW}$ (Calculated CHF) (-)

33%

-33%

1.00E-01, 1.00E-02, 1.00E-03 (y-axis)

1.000E-03, 1.000E-02, 1.000E-01 (x-axis)

$$q^*_{CHF,3NEW} = 0.7 \frac{A}{A_{II}} \frac{\sqrt{W/\lambda}}{\left\{1 + \left(\rho_g / \rho_\ell\right)^{1/4}\right\}^2} \left\{1 + \Delta T^*_{SUB,in}\right\}$$

233

Comparison between measured FE heat flux (CHF) at ORNL and CHF predicted by Gambill & Weatherhead

q CHF predicted by Gambill & Weatherhead (MW/m²)

TSD : Test Section Design

- ▲ TSD-3/A
- ▨ TSD-3/B
- ◉ TSD-3/C
- ◇ TSD-3/D
- ▨ TSD-3/D True CHF
- ▨ TSD-3/E
- ▨ TSD-3/E True FE
- + TSD-3/F
- + TSD-3/F True FE
- ✳ TSD-3/G
- ✳ TSD-3/G True FE
- —— Q″CHFpredicted=Q″FEmeas
- ---- +20% line
- ········ -20% line

234