Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Improvement of CHF Correlation for the Narrow Rectangular Channel under the Downward Flow Condition

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1. Introduction

One of the most important thermal hydraulic phenomena considered in thermal hydraulic design of research reactor is critical heat flux (CHF). Up to present, several investigations have been carried out to predict the CHF for narrow rectangular channels. Among these, Kaminaga [1] proposed CHF model used to design research reactors such as Japanese research reactor No. 2, 3, 4 (JRR-2, 3, 4), Japanese material test reactor (JMTR), etc. Kaminaga model consists of three correlations according to mass flux conditions which result in different CHF mechanisms in narrow rectangular channel. However, it was found in our investigation that Kaminaga correlations do not consider properly the effect of the gap size on the CHF in the narrow rectangular channels. Additionally, they do not cover wide range of flow condition for research reactor [2].

The objective of this study is to improve the Kaminaga CHF correlations for both sides heating in the narrow rectangular channel which simulates a subchannel of plate-type fuels in the research reactor.

2. Methods and Results

2.1 Kaminaga correlations [1]

Kaminaga proposed correlations to predict CHF in narrow rectangular channel as following equations:

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

$$q^*_{CHF,2} = \frac{A}{A_H}\Delta T^*_{SUB,in}G^* \tag{2}$$

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

$$q^*_{CHF} = \max\left(\min\left(q^*_{CHF,1},\, q^*_{CHF,2}\right),\, q^*_{CHF,3}\right) \text{ for downflow} \tag{4}$$

2.2 Experiment data

To evaluate and improve Kaminaga correlations, we constructed experimental database obtained in the narrow rectangular channel as summarized in Table I.

Table I: Experiment data investigated in this study

Author	Mass flux (kg/m^2s)	Dimension (W x S x L, mm)
Present [2]	0 ~ 2,379	66.6 x 2.35 x 640(A), 44.6 x 2.58 x 182(B)
Mirshak [3]	5,000 ~ 13,000	65.0 x 3.30 x 489
Kureta-Akimoto* [4]	846 ~ 15,100	5~20 x 0.2~3.0 x 50~200
Kim-Suh* [5]	0	15 x 1~10 x 35

*Experiment data to investigate effect of gap size on the CHF

2.3 Improvement of correlations

Geometry effect

In a narrow rectangular channel, not only hydraulic diameter but also channel gap affects the CHF. If the bubble size in the channel is larger than the gap size, the bubbles can block the flow passage and this phenomenon promotes the occurrence of CHF. Fig. 1(A) shows the normalized CHF according to gap size. The CHF increases as the gap size increases. If the dimensionless gap size exceeds a certain threshold, its effect on the CHF disappears.

The CHF correlation using inlet condition should be considered effect of channel L/D on the CHF. However, Kaminaga correlation for high mass flux region does not consider it. Thus, the L/D effect on the CHF reported by Tanaka et al. [6] is added to the original correlation.

Inlet subcooling effect

In low mass flux region, the Kaminaga correlation predicts the CHF using the inlet subcooling regardless of mass flux. Fig. 1(B) shows the normalized CHF according to inlet subcooling. Although the data are scattered, the normalized CHF has a low value under low subcooling condition. In addition, the normalized CHF increases as the subcooling increases.

Mass flux effect

The Kaminaga correlation in medium and high mass flux region does not consider the effects of the velocity or mass flux. To improve this, normalized CHF is analyzed according to dimensionless mass flux. Fig. 1(C) shows the normalized CHF according to dimensionless mass flux in medium mass flux region.

The normalized CHF decrease with increasing dimensionless mass flux for all cases. Fig. 1(D) shows the effect of mass flux on normalized CHF considering geometry effect in high mass flux region. Differently trend in the medium mass flow region, the normalized CHF increases as the mass flux increases.

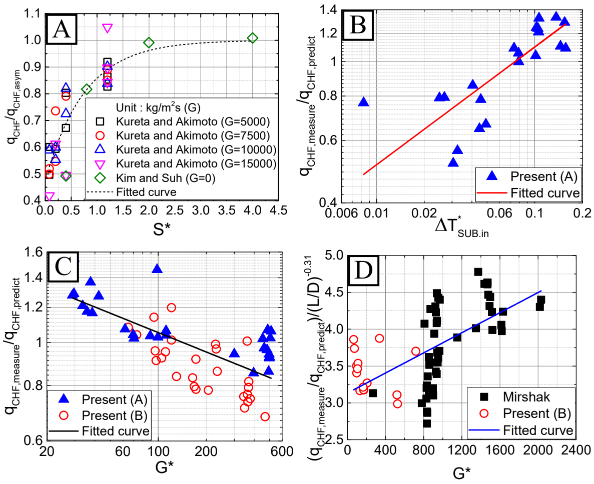

Fig. 1. Effect of gap size (A), inlet subcooling (B), mass flux (C, D) on CHF

2.4 Improved correlation

The improved correlations are proposed as Eq. (5) ~ (8) and Table II shows applicable conditions of the improved correlations. The improved correlations consider the effect of channel gap, mass flux and inlet subcooling, which were considered improperly in original correlations. In addition, the effect of the geometry which was not considered in the high mass flux region has been added to the correlation.

$$q^*_{CHF,\mathrm{low}} = 1.652\frac{A}{A_H}\cdot\frac{\sqrt{W/\lambda}}{\left\{1+\left(\rho_g/\rho_l\right)^{1/4}\right\}^2}\left(\Delta T^{*0.332}_{SUB,in} + 3\Delta T^{*1.332}_{SUB,in}\right) \quad (5)$$

$$q^*_{CHF,\mathrm{mid}} = 2.053\frac{A}{A_H}\Delta T^*_{SUB,in}G^{*0.855} \quad (6)$$

$$q^*_{CHF,\mathrm{high}} = 1.567\times10^{-2}\left|G^*\right|^{0.611}\left(1+\frac{5000}{\left|G^*\right|}\Delta T^*_{SUB,o}\right) \times\left(1+2.178\times10^{-4}G^*\right)\left(L/D\right)^{-0.31} \quad (7)$$

$$q^*_{CHF} = \max\left(\min\left(q^*_{CHF,\mathrm{mid}},\ q^*_{CHF,\mathrm{high}}\right),\ q^*_{CHF,\mathrm{low}}\right)\times C_{gap} \quad (8)$$

$$C_{gap} = 1-0.52\times0.27^{S^*}$$

Table II: Applicable conditions

Parameter	Range
Mass flux (kg/m²s)	0 ~ 15,000
Inlet subcooling (K)	5 ~ 78
Outlet pressure (kPa)	120 ~ 224
Gap size (mm)	0.2 ~ 10
L/D	40 ~ 140

2.5 Evaluation of improved correlation

Fig. 2 shows the comparison of the original correlations and the improved correlations for available experimental data. The original correlations have 17.56% for the RMS (Root Mean Square) error and the improved correlations shows 16.36% for the RMS error. Table III shows assessment result of the improved correlations using available experimental data. Most RMS errors are occurred by low mass flux data with large scattering. It implies that accurate experimental data is still required for the low mass flux condition.

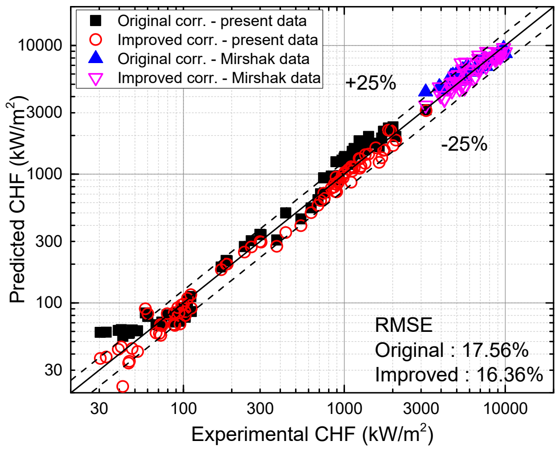

Fig. 2. Comparison of CHF between prediction and the experimental results with all available data

Table III: Assessment result of improved CHF correlation

Database	Avg. error	RMS error
Present study	9.30	19.80%
Mirshak et al.	0.35	12.06%
Total	5.74%	16.36%

3. Conclusions

In this study, the effects of gap size, inlet subcooling, mass flux and channel L/D on the CHF are investigated to improve the Kaminaga correlation. Finally, improved correlation was proposed for the design and safety analysis of research reactor. The improved correlation is applicable to the conditions for mass flux between 0 to 15,000 kg/m²s, inlet subcooling between 5 to 78 K, the outlet pressure 120 to 224 kPa, the channel gap size between 0.2 to 10 mm and L/D between 40 to 140.

NOMENCLATURE

A : Flow area (m²)
A_H : Heated area (m²)
D : Hydraulic diameter (m)
G : Mass flux (kg/m²s)
G^* : Dimensionless mass flux

$\left(= G \Big/ \sqrt{\lambda\left(\rho_l - \rho_g\right)\rho_g g} \right)$

g : Acceleration of gravity (m/s^2)

h_{fg} : Latent heat (kJ/kg)

L : Channel length (m)

q_{CHF} : Critical heat flux (kW/m^2)

q^*_{CHF} : Dimensionless CHF

$\left(= q_{CHF} \Big/ h_{fg}\sqrt{\lambda\left(\rho_l - \rho_g\right)\rho_g g} \right)$

S : Gap size (m)

S^* : Dimensionless gap size

$\left(= S \Big/ \left\{ \sigma \big/ \left(\rho_l - \rho_g\right) g \right\}^{1/2} \right)$

$\Delta T_{SUB,in}$: Subcooling (K)

$\Delta T^*_{SUB,in}$: Dimensionless subcooling

$\left(= C_p \Delta T_{SUB} \big/ h_{fg} \right)$

W : Channel width of rectangular channel (m)

ρ_g, ρ_l : Density of gas and liquid (kg/m^3)

σ : Surface tension (N/m)

λ : Laplace critical wave length (m)

$\left(= \left\{ \sigma \big/ \left(\rho_l - \rho_g\right) g \right\}^{1/2} \right)$

ACKNOWLEDGMENTS

This work was supported by the Nuclear Research & Development Program of the NRF (National Research Foundation of Korea) grant funded by the MSIP (Ministry of Science, ICT and Future Planning) and Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC) and Republic of Korea (Grant code: NRF-2015M2B2A9029358, No.1305011).

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