Investigation of Flow Transient CHF for Narrow Rectangular Channel under Downward Flow Condition

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1. Introduction

The flow and geometry characteristics of a narrow rectangular channel simulating the subchannel of plate-type fuel elements for a research reactor affects the critical heat flux (CHF), which is the most important parameter for the thermal-hydraulic design and safety analysis. However, most of existing CHF correlations are developed for circular tubes. Because of this fact, they have some limitations when they are applied to the narrow rectangular channels for reactor core of the research reactor. Moreover, CHF is currently predicted based on the steady-state CHF correlation even though the flow condition for the design basis accidents are transient. However, there are few studies on the flow transient CHF in the event of accidents such as loss of flow accident (LOFA). Some previous investigators[1, 2, 3] have reported that the flow transient affects greatly the CHF in circular tubes. The significant influence of flow transient on the CHF is also expected in the narrow rectangular channel. Therefore, it is necessary to develop a correlation of flow transient CHF in the narrow rectangular channel for the enhancement of prediction capability for the plate-type fuel.

2. Methods and Results

2.1 Experimental data

Experimental data from Celata et al.[1] and Kim et al.[4, 5] were used to develop flow transient CHF correlation in the present study. The Celata R-12 experiments were carried out over a wide range of flow conditions for various thermal-hydraulic parameters, as shown in Table I. Therefore, these data are suitable for parametric study of the flow transient CHF.

Table I: Experiment conditions of data set by Celata et al.[1]

Parameter	Range
Initial mass flux (kg/m^{2}s)	1,000, 1,250, 1,470
Inlet subcooling (°C)	0 ~ 30
Outlet pressure (kPa)	1,200 ~ 2,750
Half-flow decay time (s)	0.4 ~ 13.0

Experimental data from Kim et al. were obtained under flow transient conditions for the narrow rectangular channel simulating the subchannel of plate-type fuel, as shown in Table II.

Table II: Experiment conditions of data set by Kim et al.[5]

Parameter	Range
Mass flux (kg/m^{2}s)	950 ~ 4,700
Inlet temperature (°C)	37
Outlet pressure (kPa)	170
Time constant (s)	1 ~ 90

2.2 Parameters relate to flow transient

The transient time parameter proposed by Celata is dependent on the initial value as follows.

$$\tau = t_{\mathrm{h}} \Big/ \left(\rho_{\mathrm{f,init}} L / G_{\mathrm{init}} \right) \tag{1}$$

In order to consider the characteristics of the flow transient, flow reduction rate was defined, which is a variable without changing according to transient time, as follows.

$$\alpha = -\frac{1}{G}\frac{dG}{dt} \tag{2}$$

The flow reduction rate is defined as the ratio of the reduction of mass flux to the current mass flux, which does not change with time. And, it has the same value at the inlet and outlet at the given time. Therefore, it is appropriate to use it as a parameter to characterze the flow transient for analysis. If the mass flux according to time follows an exponential function, it is expressed by the initial mass flux(G_{init}, m/s^2) and the flow reduction rate(α, s^{-1}) as follows.

$$G(t) = G_{\mathrm{init}} \exp^{-\alpha t} \tag{3}$$

Since the mass flux for flow transient condition is determined by the initial mass flow flux and the flow reduction rate, the influence of the initial mass flux and the flow reduction rate on the CHF should be evaluated. Fig. 1 shows the influence of the initial mass flux and the flow reduction rate on the flow transient CHF for Celata R-12 data. The mass flux ratio is affected by the flow reduction rate but not the initial mass flux. Therefore, the flow transient CHF can be analyzed by the parameters affecting the steady-state CHF and the flow reduction rate.

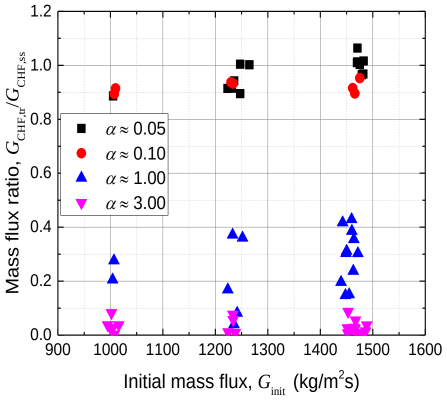

Fig. 1. Influence of the initial mass flux and the flow reduction rate on the flow transient CHF

2.3 Boundary condition

In previous studies[2, 3], mass flux ratio was used to quantify the influence of flow transient on the CHF. However, the mass flux ratio does not directly represent the CHF value. Therefore, in this study, we develop a correlation that predicts the CHF ratio. The boundary conditions of the CHF ratio are as follows.

$$\frac{q_{\mathrm{CHF,tr}}}{q_{\mathrm{CHF,ss}}} = \begin{cases} 1, & \alpha = 0 \\ C, & \alpha = \infty \end{cases} \qquad (4)$$

If the flow rate reduction is zero, it implies steady-state, and thus the value of flow transient CHF is same with that of steady-state CHF. If the flow rate reduction rate is infinite, it means a very fast transient that the mass flux instantaneously becomes zero. At this time, the CHF ratio converges to specific constant, *C*. It implies the value of CHF for fast transient is same with *C* times of pool-boilng CHF value.

2.4 Dimensionless velocity

Fig. 2 and 3 show the CHF ratio according to flow reduction rate and mass flux, respectively. As the flow reduction rate increases, the CHF ratio increases. And it decreases as the mass flux increases. Since the flow reduction rate and the mass flux have the greatest influence as described above, a dimensionless velocity is proposed to consider these two parameters as follows.

$$j^* = \frac{j_{\mathrm{f}}}{\alpha \cdot l_{\mathrm{c}}} = \frac{G/\rho_{\mathrm{f}}}{\alpha\sqrt{\sigma/\left(\rho_{\mathrm{f}} - \rho_{\mathrm{g}}\right)g}} \qquad (5)$$

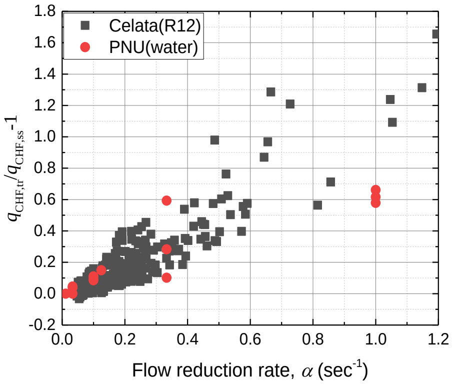

Fig. 2. CHF ratio according to flow reduction rate

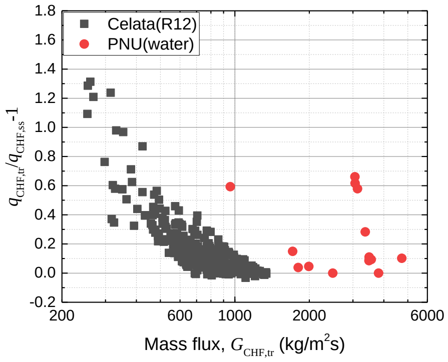

Fig. 3. CHF ratio according to mass flux

2.5 Development of flow transient correlation

Fig. 4 shows the CHF ratio according to the dimensionless velocity. As the dimensionless velocity increases, the CHF ratio decreases. It should be noted that the CHF ratio is also affected by pressure and fluid properties. To account for these two effects, the CHF ratio according to the reduced pressure and the Prandtl number is investigated. The influence of the reduced pressure on the specific dimensionless flow region(4000 $<j^*<$7000) is shown in Fig. 5. It shows the CHF ratio increases as the reduced pressure increases, and it is proportional to $(p_r + 0.1)^{2.65}$. Fig. 6 shows the CHF ratio according to the Prandtl number taking into account the fluid properties of R-12 and water. As the Prandtl number increases, the CHF ratio decreases. The Prandtl number is a dimensionless number representing the ratio of momentum transfer to heat transfer. The above result indicates that the CHF ratio decreases as the momentum transfer increases and the heat transfer decreases. The correlation was developed as Eq. (6) by regression analysis with the form of a logistic function satisfying the boundary condition of Eq. (4).

$$\frac{q_{\mathrm{CHF,tr}}}{q_{\mathrm{CHF,ss}}}=1+\frac{3.13}{1+\dfrac{j^{*}\left(p_{\mathrm{r}}+0.1\right)^{2.65}}{2810\left(\mathrm{Pr}-1.3\right)^{2.35}}} \qquad (6)$$

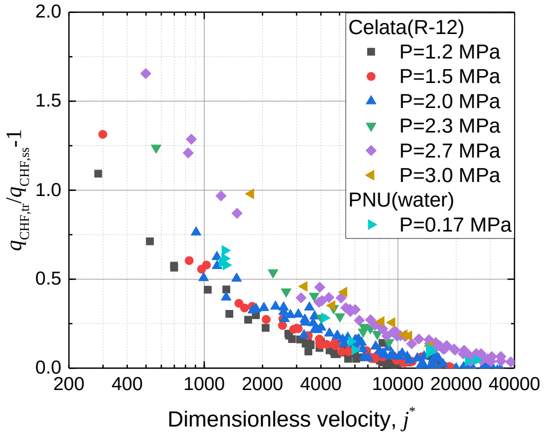

Fig. 4. CHF ratio according to dimensionless velocity

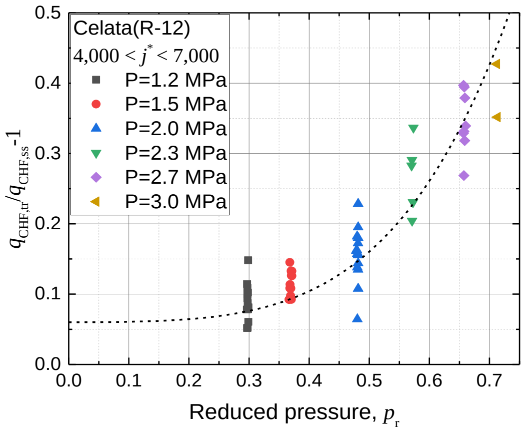

Fig. 5. CHF ratio according to reduced pressure

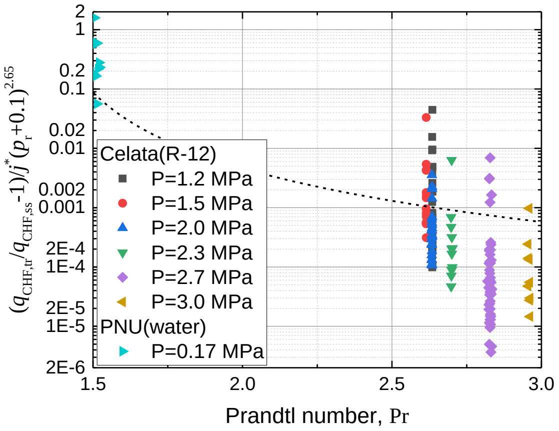

Fig. 6. CHF ratio according to Prandtl number

The developed correlation predicts the CHF ratio of 1 in the slow transient condition in which the dimensionless velocity becomes infinite. In the fast transient in which the dimensionless velocity approaches zero, the CHF ratio becomes 4.13. This implies that under extremely fast transient conditions, the CHF is 4.13 times of the pool-boiling CHF. Table III shows the applicable conditions of the developed flow transient CHF correlation. Fig. 7 shows comprison of the CHF ratio between prediction and experimental data. The developed correlation shows an average error of 0.04% and a root mean square (RMS) error of 3.46% for the experimental data.

Table III: Applicable conditions of correlation

Parameter	Range
Mass flux (kg/m^{2}s)	0 ~ 4,700
Inlet temperature (°C)	0 ~ 78
Outlet pressure (kPa)	170 for water 1,200 ~ 2,750 for R-12
Flow reduction rate (s^{-1})	0.1 ~ 2.5
Hydraulic diameter (mm)	4.54 ~ 7.72
L/D	40 ~ 300

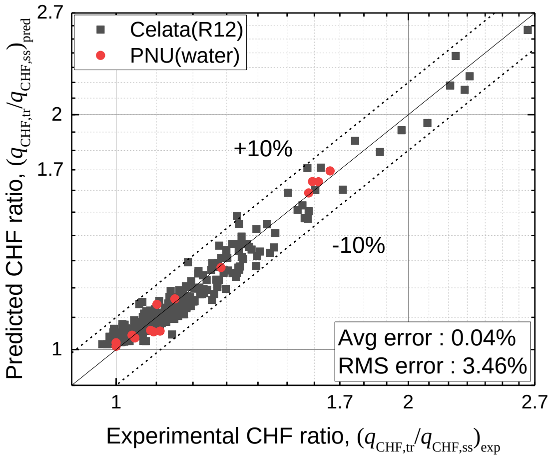

Fig. 7. Comparison of flow transient CHF ratio between prediction and experimental data

3. Conclusions

In this study, the flow transient CHF was investigated. To develop the transient CHF correlation, the R-12 data obtained by Celata et al. [1] and water data obtained by Kim et al. [5] were analyzed. From analysis results, the dimensionless velocity was proposed to consider influence of mass flux and flow reduction rate on the CHF. The developed correlation is applicable to water in the narrow rectangular channel and R-12 in a tube for flow reduction rates 0.1 ~ 2.5 s^{-1} and showed an average error of 0.04% and RMS error of 2.99%.

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