Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Flow boiling CHF model development in downward facing curved rectangular channel under almost saturated condition: focus on void fraction

Jun Yeong Jung [a], Min Suk Lee [a], Jung Hyun Song [a,b], Yong Hoon Jeong [a*]
[a] *Department of Nuclear and Quantum Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeong*
[b] *Current affiliation: Mechatronics R&D Center, Samsung Electronics, Hwasung 18448*
[*] *Corresponding author: jeongyh@kaist.ac.kr*

1. Introduction

The critical heat flux (CHF) refers to the maximum heat flux in the nucleate boiling heat transfer mode. When a heating surface heat flux exceeds it, the heat transfer mode is converted into film boiling heat transfer mode. Since the heat transfer coefficient of the film boiling heat transfer is much lower than that of the nucleate boiling heat transfer, the temperature of the heating surface rapidly rises, which may lead to extreme damage to the heating surface. However, the higher heat flux makes the more energy transfer, and it means the better energy efficiency of the heat transfer system in the industrial area. Therefore, it is economical and safe to increase the surface heat flow rate as much as possible below the CHF.

For this reason, a nuclear industry has made efforts to predict the CHF to guarantee the both safe and efficiency not only in normal operation and but also in accident situations. First, under normal operating conditions, the fuel rods are vertically standing pipes, and the coolant circulates around them and heat transfer occurs in the core. Since the rod geometry, coolant temperature, pressure, and flow rate are clear, it is possible to predict relative comfortably, and related research and data are abundant.

On the other hand, in-vessel retention external reactor vessel cooling (IVR-ERVC), one of the severe accident mitigation strategy, has a unique shape called a downward facing heat transfer. So, it is difficult to predict a CHF because the behavior of vapor is totally different from pipe flow and upward facing heat transfer. In particular, in the upward facing heat transfer, vapor leaves the heating surface due to buoyancy, but in the downward condition, it attaches to the heating surface and move along with the coolant flow at the same time. Therefore, since the generated vapor continue to affect the heating surface, the vapor behavior is one of the important factors[1] in predicting the CHF. The main factors are the length, thickness, velocity, and amount of vapor near the heating surface[2][3]. Among them, in this study, the main concern is to properly predict the amount of bubbles generated, that is, void fraction. It seems easily that the vapor generation amount is simply calculated by the energy conservation given from the heating surface. In reality, however, it is not simple because the vapor generation and disappearance (condensation) occur simultaneously. In addition, in the case of the downward facing heat transfer, the generated vapor concentrated near the heating surface by the buoyancy to form the two-phase boundary layer. In other words, it is a non-uniform flow condition in which vapors are concentrated near the heating surface. However, the existing CHF correlations had not properly considered this non-uniform condition. In the next chapter, explanations of previous studies related to the above-described content are described.

2. Literature survey

This chapter describes the CHF correlation for the downward facing heat transfer. One of the most famous experiments for measuring the CHF of ERVC is the ULPU experiment[4], [5]. This study is significant in that the CHF experiment was conducted under conditions close to reality using a large experimental facility and natural circulation. This paper presented the CHF correlation (Eq. 1), and it is a mathematical correlation with the orientation angle (θ) of the heating surface as the only variable. Although it is a widely used correlation, the void fraction, which is the focus of this study, was not considered.

$$q''_{CHF} = 490 + 30.2\theta - 0.888\theta^2 + 1.35 \cdot 10^{-2}\theta^3 - 6.65 \cdot 10^{-5}\theta^4 \qquad \text{Eq. 1}$$

Next is the correlation developed by the MIT[6]. This correlation was also based on mathematical techniques with simple physical approach, and used pressure, mass flux, quality (which can be converted to void fraction), and orientation angle as variables.

$$CHF = Y_1\left(\frac{P}{P_c}\right)^{Y_2}\left(\frac{G}{10^3}\right)^{Y_3}\left[1-Y_4\left(\frac{G}{10^3}\right)^{0.5}x_e\right]\left[\frac{3}{2}-\frac{1}{4}\cos(2\theta)\right] \qquad \text{Eq. 2}$$

Where
P: pressure
G: mass Flux
X_e: exit quality
θ: orientation angle
Y_1~Y_4: constant

The SULTAN[7] was an experiment performed under a wide experimental condition and presented a correlation equation as shown in Eq 3. The SULTAN correlation can predict wide experimental variables, but it predicts CHF only with mathematical techniques based on the variables. From A_0 to A_4, they are mathematical equation based on input variables.

$$CHF = A_O(E,P,G) + A_1(E,G)*X + A_2(E)*X^2 + A_3(E,P,G,X)*\theta + A_4(E,P,G,X)*\theta^2 \quad \text{Eq. 3}$$

Where
- P: pressure
- G: mass Flux
- X: local equilibrium quality
- E: flow channel gap
- θ: orientation angle

In addition to the aforementioned studies, there are many other studies[8]–[12] on CHF correlation. Some papers have use mechanical principle to predict the CHF. However, their scope is not appropriate for ERVC, or dependency of correction coefficient was so great that it was not introduced in this paper.

3. CHF model development

3.1 Assumptions

(1) It is considered that CHF occurred when all liquid layer evaporated while the vapor passed through the heating surface.
(2) The maximum thickness of the liquid film is limited by Helmholtz instability.
(3) The velocity distribution of the coolant follows Karman's wall function.
(4) The vapor equivalent diameter is calculated using the void fraction and the cross-sectional area of the flow channel. Do not use the bubble departure diameter of nucleate boiling.
(5) The vapor length is assumed to be the maximum length due to Helmholtz instability.

3.2 CHF model based on liquid sublayer dry out

Considering the environment of IVR-ERVC, this paper considered the 'liquid layer dry out' model as the most suitable physical phenomenon for predicting the CHF. This mechanism assumes that there is a thin liquid film between the vapor and the heat transfer surface, and the CHF occurs when all of this liquid film evaporates during the time the vapor passes through the surface (Assumption 1). Figure 1 shows the conceptual diagram of vapor with some major parameters. The meaning of parameters is summarized in Table 1.

The CHF correlation consist of the following Eq. 4. Under the saturation condition, Eq. 4 has no need to consider the subcooling enthalpy[13]. However, this study wants to cover subcooled condition, so Eq. 4 has the subcooling enthalpy term. This correlation considering the coolant subcooling, and to predict the CHF, liquid sublayer thickness, vapor length and velocity are necessary.

$$q''_{CHF} = \frac{\rho_l \delta_m (h_{fg} + h_{sub-cooling})}{l} u_g \quad \text{Eq. 4}$$

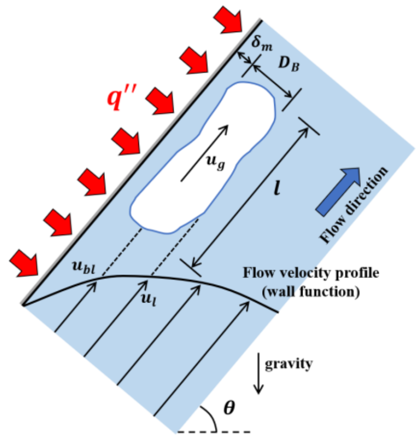

Figure 1. Conceptual diagram of vapor near the heating surface

Table 1. Meaning of the parameters

Parameter	Meaning
u_g	Vapor mean velocity
δ_m	Liquid sublayer thickness
D_B	Equivalent vapor diameter
l	Vapor length
u_{bl}	Coolant velocity at the center of vapor
u_l	Coolant velocity at the outer edge of vapor
θ	Heating surface orientation angle
q''	Heat flux

It is assumed that the thickness of the liquid film is proportional to the Helmholtz wavelength[14] like Eq. 5. However, the method of calculating the thickness of the liquid film with Helmholtz wavelength was developed under an upward facing pool boiling heat transfer condition, so a correction constant (C_1) was added.

$$\delta_m = C_1 \sigma \rho_g \left(1 + \frac{\rho_g}{\rho_l}\right)\left(\frac{\rho_g}{\rho_l}\right)^{0.4}\left(\frac{h_{fg}}{q''_{CHF}}\right)^2 \quad \text{Eq. 5}$$

It is assumed that the vapor length (Eq. 6) is also limited by the Helmholtz instability. At this time, it was said that instability was caused by the difference between the vapor average speed and the that of coolant. The vapor velocity was calculated using the force balance acting on the vapor like Eq. 7.

$$l = \frac{2\pi\sigma(\rho_l + \rho_g)}{\rho_l \rho_g (u_g - u_l)^2} \qquad \text{Eq. 6}$$

$$\frac{\pi}{4} D_B^2 l g(\rho_l - \rho_g)\sin\theta = \frac{1}{2}\rho_l C_D (u_g - u_{bl})^2 \frac{\pi D_B^2}{4}$$

$$\text{where} \quad C_D = \frac{2}{3}\left[g(\rho_l - \rho_g)\frac{D_B^2}{\sigma}\right]^{0.5} \qquad \text{Eq. 7}$$

In order to solve Eq. 6, 7, the coolant velocities (u_l, u_{bl}) are required. As mentioned in the assumption, it was assumed that the coolant velocity distribution followed Karman's wall function. The coolant velocities (u_l, u_{bl}) are calculated like Eq. 8, and two-phase Reynold number is essential.

$$u_l = C_2 Re_{TP}^{-0.1} \frac{G}{\rho_l}\left\{ln\left[\frac{0.152 Re_{TP}^{-0.1} G(\delta_m + D_B)}{\mu_l}\right] - 0.61\right\}$$

$$u_{bl} = C_2 Re_{TP}^{-0.1} \frac{G}{\rho_l}\left\{ln\left[\frac{0.152 Re_{TP}^{-0.1} G(\delta_m + D_B/2)}{\mu_l}\right] - 0.61\right\} \qquad \text{Eq. 8}$$

where

$$Re_{TP} = \frac{G D_h}{\mu_l}\frac{1 - x}{1 - \alpha}$$

In the past, only thermal equilibrium quality was used to calculate the two-phase Reynolds number. However, in case of this quality calculation method, the quality became negative under conditions where the subcooling of the working fluid was large or the CHF was low. Due to negative quality, the void fraction also became negative, it was simulating a non-physical situation. As a result, as described above, the CHF model calculation of the CHF model did not work under conditions of low inclination angle (low CHF). However, it has been confirmed through visualization experiments that vapor are actually being generated and have a certain amount of void fraction. In other words, since vapor are unevenly distributed due to the characteristics of the downward facing heating geometry, there is a limit to simulating this situation with the existing equilibrium quality method.

Therefore, in this study, the following new quality and void fraction calculation methods[15] were used. Equation 9 shows the true quality (x) and void fraction (α).

$$x = \frac{x_{eq} - x_\lambda \times \exp(\frac{x_{eq}}{x_\lambda} - 1)}{1 - x_\lambda \times \exp(\frac{x_{eq}}{x_\lambda} - 1)} \quad x_{eq} = \frac{h - h_{fg}}{h_{fg}}$$

$$\alpha = \frac{x}{\left(1.35 - 0.35\sqrt{\frac{\rho_g}{\rho_f}}\right)\left(x\frac{\rho_f - \rho_g}{\rho_g} + \frac{\rho_g}{\rho_f}\right) + 1.41\frac{\rho_g}{G}\left(\frac{\sigma g(\rho_f - \rho_g)}{\rho_f^2}\right)^{0.25}} \qquad \text{Eq. 8}$$

$$\begin{cases} x_\lambda = -0.0022^{q'' C_p D_h}/_{k_f h_{fg}} & for\ Pe < 70{,}000 \\ x_\lambda = -153.8^{q''}/_{G h_{fg}} & for\ Pe \geq 70{,}000 \end{cases} \quad Pe = \frac{G D_h C_p}{k_f}$$

Although the above method requires somewhat complex calculations, the quality and void fraction could be properly calculated even at a low orientation condition. This CHF model have two correction constants, and C_1 and C_2 are 0.013 and 3.0 respectively. They are decided based on the try and error.

4. Results

The CHF model described in this paper significantly improves the method of calculating quality and void fractions compared to the previous one. This allows the model to operate even at a low inclination angle. In the previous method, it was operated only at 90° and a part of the 60°, but in the improved method, the CHF could be calculated even at the 30° orientation angle. However, it can be seen that some CHF are still overestimated at the 30° orientation.

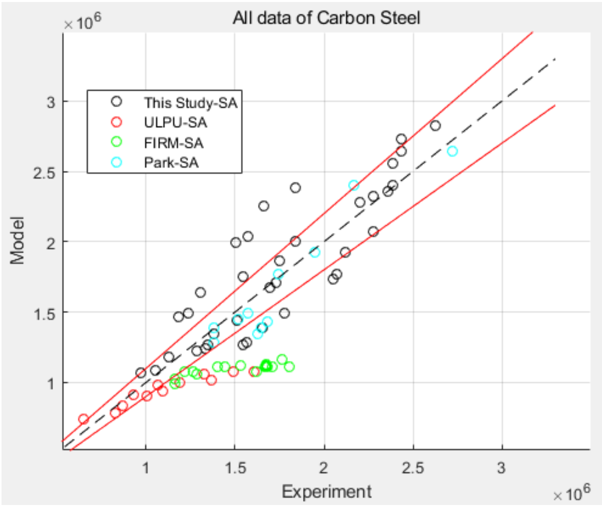

Figure 2. Modified CHF model results of SA508

For comparison, other experimental results were predicted by the CHF model which was developed in this paper. Figure 2 shows the CHF model prediction results of SA508. Although there is a tendency to underestimate the FIRM [16] results, it can be seen that the results of other papers predict fairly well [17], [18]. Considering that the deviation of the CHF value is large because carbon steel (SA508) is a metal in which surface oxidation easily occurs, it can be seen that the above CHF model prediction results are very well. Table 2 shows the results of the RMS error of this CHF model for each experiment. Because the Park study conducted at only 90 ° orientation angle, its RMS error was smallest among these studies.

Table 2. RMS error for each study

This study	ULPU	FIRM	Park
15.3 %	17.8 %	28.0 %	9.4 %

Next, for comparison with the CHF correlation proposed in other papers, the prediction results of ULPU and MIT correlation were confirmed. The ULPU correlation is based on experiments conducted on the actual reactor vessel radius curvature, and the MIT correlation is developed for a wide thermal hydraulics range, so the above two correlation equations were selected in this paper. Figure 3, 4 shows the model results of ULPU and MIT respectively.

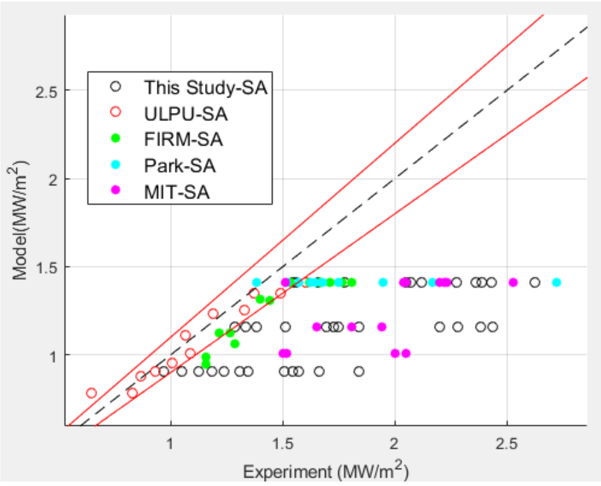

Figure 3. ULPU CHF results of SA508

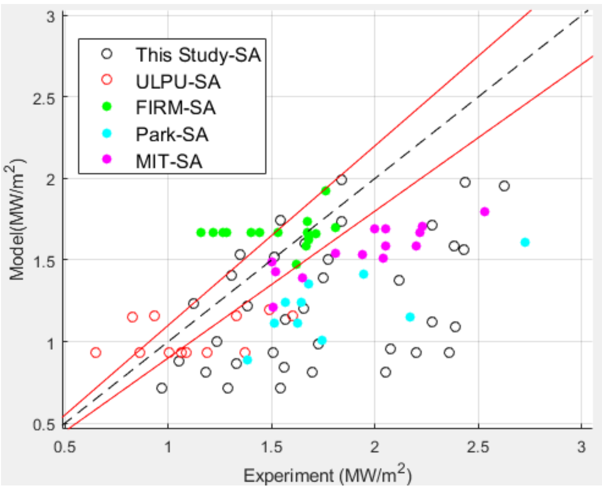

Figure 4. MIT CHF results of SA508

In the case of the ULPU correlation, the orientation angle of the heat transfer surface is the only input variable. Therefore, the same CHF value was predicted if the angle was the same regardless of all other conditions. As a result, it is difficult to predict the results of other experiments. Second, the MIT correlation used pressure, mass flux, outlet dryness, and orientation angle as input variables. Thanks to that, the correlation predicted other experimental results well to some extent. However, most experimental results tended to be underestimated. This is considered as a limitation caused by the model itself being built based on a mathematical trend line, although the MIT correlation had various input variables.

5. Conclusions

This paper introduced the KAIST CHF model which developed based on the mechanistical principle. Based on the above results, this paper concluded as follows.

(1) At low orientation angle, properly predicting quality and void fractions is important for the CHF model.

(2) The mechanistical CHF model showed good results in predicting not only their own results but also other experimental results.

(3) However, as there is a tendency in the CHF prediction results depending on the orientation angle, it is necessary to appropriately consider the angle effect in the CHF model development in the future.

At the same time, there is a limitation related on the heater material. In this study, the CHF results carried out as a carbon steel heater were used for the CHF model development. To do this, the values of C1 and C2 were optimized accordingly. In other words, the heating surface material characteristics are not physically considered in the CHF correlation. Therefore, the correction constant should be newly optimized depending on the heater material.

Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea. (No.2003004)

REFERENCES

[1] F. B. Cheung, K. H. Haddad, and Y. C. Liu, "Critical Heat Flux (CHF) phenomenon on a downward facing curved surface," 1997, [Online]. Available:

http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=491560.

[2] I. M. C.H. Lee, "A mechanistic critical heat flux model for subcooled flow boiling based on local bulk flow conditions," *Int. J. Multiph. Flow*, vol. 14, no. 6, pp. 711–728, 1988, doi: 0301-9322.

[3] J. E. Galloway and I. Mudawar, "CHF mechanism in flow boiling from a short heated wall-I. Examination of near-wall conditions with the aid of photomicrography and high-speed video imaging," *Int. J. Heat Mass Transf.*, vol. 36, no. 10, pp. 2511–2526, 1993, doi: 10.1016/S0017-9310(05)80190-5.

[4] T. N. Dinh, J. P. Tu, T. Salmassi, and T. G. Theofanous, "Limits of coolability in the AP1000-related ULPU-2400 configuration V facility," in *Proceedings of the tenth international topical meeting on nuclear reactor thermal hydraulics*, 2003, p. 1CD-ROM, [Online]. Available: http://inis.iaea.org/search/search.aspx?orig_q=RN:36067256.

[5] T. G. Theofanous and S. Syri, "The coolability limits of a reactor pressure vessel lower head," *Nucl. Eng. Des.*, vol. 169, no. 1–3, pp. 59–76, 1997, doi: 10.1016/s0029-5493(97)00024-1.

[6] M. Trojer *et al.*, "A margin missed: The effect of surface oxidation on CHF enhancement in IVR accident scenarios," *Nucl. Eng. Des.*, vol. 335, no. March, pp. 140–150, 2018, doi: 10.1016/j.nucengdes.2018.05.011.

[7] S. Rougé, I. Dor, and G. Geffraye, "Reactor Vessel External Cooling for Corium Retention SULTAN Experimental Program and Modelling with CATHARE Code," *Work. in-vessel core debris Retent. Cool.*, pp. 351–363, 1998.

[8] Y. Katto, "A physical approach to critical heat flux of subcooled flow boiling in round tubes," *Int. J. Heat Mass Transf.*, vol. 33, no. 4, pp. 611–620, 1990, doi: 10.1016/0017-9310(90)90160-V.

[9] H. Setoodeh, W. Ding, D. Lucas, and U. Hampel, "Prediction of bubble departure in forced convection boiling with a mechanistic model that considers dynamic contact angle and base expansion," *Energies*, vol. 12, no. 10, pp. 1–29, 2019, doi: 10.3390/en12101950.

[10] J. E. Galloway and I. Mudawar, "CHF mechanism in flow boiling from a short heated wall-II. Theoretical CHF model," *Int. J. Heat Mass Transf.*, vol. 36, no. 10, pp. 2527–2540, 1993, doi: 10.1016/S0017-9310(05)80191-7.

[11] U. Jeong and S. J. Kim, "Semi-mechanistic prediction of spatial variation of local critical heat flux along a slightly inclined downward-facing surface," *Int. Commun. Heat Mass Transf.*, vol. 119, no. October, 2020, doi: 10.1016/j.icheatmasstransfer.2020.104909.

[12] W. X. Liu *et al.*, "An improved mechanistic critical heat flux model and its application to motion conditions," *Prog. Nucl. Energy*, vol. 61, pp. 88–101, 2012, doi: 10.1016/j.pnucene.2012.07.002.

[13] F. B. Cheung and K. H. Haddad, "A hydrodynamic critical heat flux model for saturated pool boiling on a downward facing curved heating surface," *Int. J. Heat Mass Transf.*, vol. 40, no. 6, pp. 1291–1302, 1997, doi: 10.1016/S0017-9310(96)00208-6.

[14] Y. Haramura and Y. Katto, "A New Hydrodynamic Model of Critical Heat Flux : Mechanism of Critical Heat Flux for Pool Boiling and Forced Convection Boiling on Submerged Bodies in saturated Liquid," *Trans. Japan Soc. Mech. Eng. Ser. B*, vol. 49, no. 445, pp. 1919–1927, 1983, doi: 10.1299/kikaib.49.1919.

[15] P. Saha and N. Zuber, "Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling.," no. January 1974, pp. 175–179, 1974, doi: 10.1615/ihtc5.430.

[16] H. Chang, T. Hu, W. Lu, S. Yang, and X. Zhang, "Experimental study on CHF using a full scale 2-D curved test section with additives and SA508 heater for IVR-ERVC strategy," *Exp. Therm. Fluid Sci.*, vol. 84, pp. 1–9, 2017, doi: 10.1016/j.expthermflusci.2017.01.018.

[17] H. M. Park, Y. H. Jeong, and S. Heo, "Effect of heater material and coolant additives on CHF for a downward facing curved surface," *Nucl. Eng. Des.*, vol. 278, pp. 344–351, 2014, doi: 10.1016/j.nucengdes.2014.07.019.

[18] T. N. Dinh, J. P. Tu, T. Salmassi, and T. G. Theofanous, "Limits of the coolability in the AP1000-related ULPU-2400 configuration V facility," *Int. Top. Meet. Nucl. React. Therm. Hydraul.*, pp. 1–14, 2003.