Predicting Critical Heat Flux under Heaving Conditions: A Methodology Integrating Transient Conduction Calculation and CHF Mechanistic Model

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Keywords : critical heat flux, heaving motion, floating nuclear power plant, simulant fluid

1. Introduction

Due to the climate crisis, the importance of carbon-free power sources has become increasingly prominent, prompting diversification in the utilization of nuclear power. In particular, Floating Nuclear Power Plants (FNPPs) represent the application of small modular reactors (SMRs) in ocean environments. This type of reactor enables a reliable supply of power to remote areas where conventional grids are difficult to access. It can also be utilized for resource development, process heat production, and the generation of hydrogen and ammonia [1, 2]. However, because the platform of the plant is subject to motion conditions, the thermal-hydraulic phenomena inside the reactor may differ from those under onshore conditions. Therefore, it is essential to evaluate the effects of motion on the safety analysis of FNPPs. Specifically, for Critical Heat Flux (CHF), which determines the thermal safety margin of the reactor core, it is necessary to experimentally investigate the motion effect on this phenomenon.

Seoul National University has been conducting experimental studies using refrigerant R134a as a simulant fluid under various heater geometries and motion conditions [3-9]. Among these studies, Yoo et al. [7-9] measured the flow boiling CHF under heaving motion conditions and proposed mechanisms for CHF variation. Though the experiments were conducted under a wide range of thermal-hydraulic and heaving conditions, further discussion is needed for cases where the heaving period is longer than the experimental conditions (3 to 5.3 s) and when the working fluid is water. In this context, this study proposed a CHF prediction methodology by integrating the transient conduction calculation and the CHF mechanistic model. Using the developed methodology, the period and fluid scaling effects were estimated.

2. Method and Results

This study proposed a methodology for predicting CHF under heaving conditions by tracking the wall temperature behavior during CHF. Using the proposed methodology, heaving CHF was calculated against the experimental setup of the previous study [9], and the period effect and fluid-scaling effect were estimated.

2.1 Overview of the proposed methodology

To predict heaving CHF, the model must account for the additional force caused by heaving motion. Among CHF mechanistic models, the liquid sublayer dryout model is particularly suitable because it is based on the force balance CHF triggering mechanism, allowing it to consider the effect of additional forces. Additionally, due to the nature of the mechanistic model, it can be used to predict CHF in both water and non-aqueous fluids.

Meanwhile, the mechanistic model alone is insufficient to predict heaving CHF. The mechanistic model, which is based on the force balance, estimates the heaving CHF corresponding to an instantaneous quasi-steady state in the oscillatory acceleration field. Under heaving conditions, however, CHF phenomena are characterized by the cyclic formation and quenching of dry patches, quenching failures due to the superheated heater wall, and subsequent temperature excursions [7]. Therefore, tracking the wall temperature is essential for predicting heaving CHF. As a result, the conduction equation is solved to monitor the heater wall temperature, with the boundary condition of the heat transfer mode determined by comparing the CHF predicted by the mechanistic model and the applied heat flux. A schematic diagram of the proposed method is shown in Fig. 1.

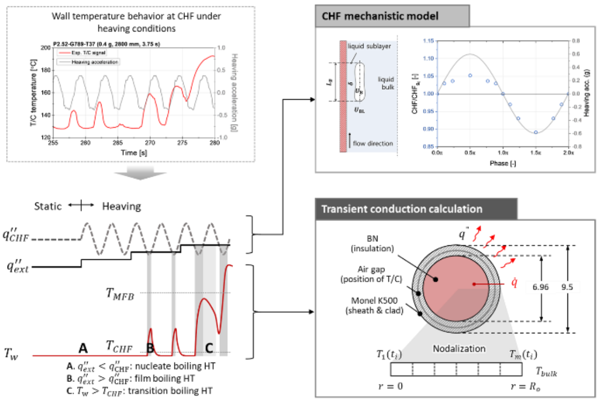


Fig. 1. Schematic diagram of proposed method

Fig. 2 illustrates the calculation flow chart for the proposed method. For the given conditions (thermal-hydraulic conditions, geometric conditions, motion conditions), the initial heat flux (q''_0) is assumed, and the calculation is initialized through steady-state conduction calculations. Next, for each calculation time (t_{cal}), the heaving acceleration (a_{HV}) is calculated, and the instantaneous CHF value under that acceleration condition, $q''_{CHF,i}$, is calculated by the mechanistic model. Then, by comparing $q''_{CHF,i}$ with the applied wall heat flux (q''_{ext}) and comparing the heater wall temperature (T_w) with the minimum film boiling temperature (T_{MFB}), the heat transfer mode and corresponding heat transfer coefficient (HTC) are determined. The models for calculating HTC are detailed in section 2.2. Using the calculated HTC as a boundary condition, transient conduction calculations are performed, and this process is repeated with a slight increase in q''_{ext} every 2 motion periods. In the calculation, the CHF$_{\mathrm{HV}}$ was determined as the heat flux at which the wall temperature rises above T_{MFB}, making surface rewetting no longer possible.

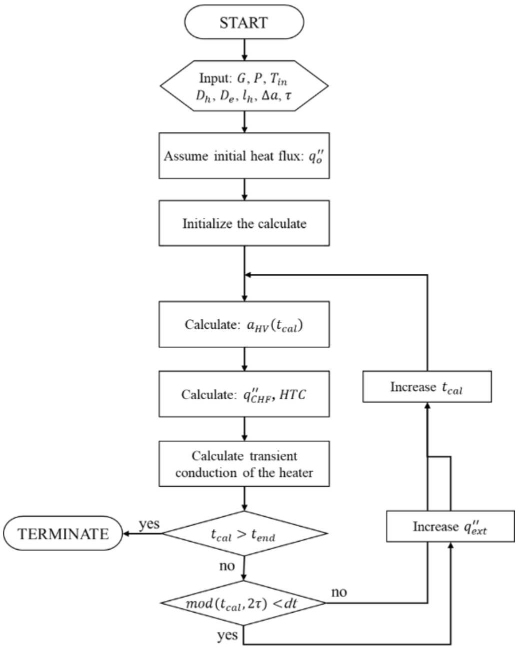


Fig. 2. Calculation flow chart for predicting heaving CHF

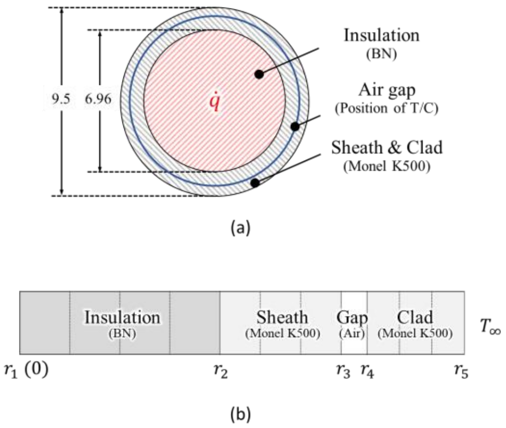


Fig. 3. Descriptions of the transient conduction calculation:
(a) Schematic of the heater rod configuration,
(b) Discretization of the heater rod for conduction calculation

2.2 Transient conduction calculation

The radial temperature distribution of the heater rod can be calculated by solving the one-dimensional conduction equation in cylindrical coordinates, as expressed in Eq. 1.

$$\rho c_P r \frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \dot{q} \cdot r \tag{1}$$

where ρ, c_P, T, k, r, and $\dot{q}$ denote density, specific heat capacity, temperature, thermal conductivity, radial position, and volumetric heat generation, respectively. The radial temperature distribution can be calculated numerically by discretization, as shown in Fig. 3.

The boundary condition for the heater's outer surface varies with the change in heat transfer mode. The heat transfer mode was determined based on a phenomenological analysis of boiling phenomena, referring to the classification map of the SPACE and TRACE codes. The heat transfer for the three modes—nucleate boiling, film boiling, and transition boiling—was calculated using the following models.

Nucleate boiling heat transfer [10]

$$HTC_{nb} = \left[\left(HTC_{nb,o}F_{nb}\right)^3 + \left(HTC_{Lt}F_{tp}\right)^3\right]^{1/3} \tag{2}$$

Film boiling heat transfer [11]

$$HTC_{fb} = Nu_{fb} \cdot \frac{k_g}{D_e} \tag{3}$$

$$Nu_{fb} = 0.023Re^{0.8}Pr^{0.4} \tag{3'}$$

Transition boiling heat transfer

$$HTC_{tb} = \xi \cdot HTC_{nb} + (1-\xi) \cdot HTC_{fb} \tag{4}$$

$$\xi = max(0.2, 1-\alpha) \cdot \left[\frac{T_w - T_{MFB}}{T_{CHF} - T_{MFB}}\right]^2 \tag{5}$$

where HTC_{nb}, $HTC_{nb,o}$, and F_{nb} denotes effective nucleate flow boiling coefficient, local nucleate pool boiling coefficient, and nucleate flow boiling correction factor. HTC_{Lt} and F_{tp} denotes Gnielinski convective coefficient based on total mass flux assumed as liquid [12] and two-phase flow multiplier. HTC_{fb}, k_g, and D_e are film boiling coefficient, thermal conductivity of vapor, and heated equivalent diameter, respectively. In addition, HTC_{tb}, ξ, T_{CHF} and T_{MFB} denote transition boiling heat transfer coefficient, weighing function, critical heat flux temperature, and minimum film boiling temperature, respectively. In the case of transition boiling, as suggested by Bjornard & Griffith [13], the fraction of the wall in contact with the liquid is assumed to be expressed as in Eq. 5. To calculate T_{MFB}, Carbajo model [14] was used. Meanwhile, for refrigerant R134a, the observed experimental values were used instead of the model due to the high uncertainty of the model with non-aqueous fluid. Detailed information can be found in the reference [9].

2.3 CHF mechanistic model for annulus channel

A mechanistic model was established to simulate the heaving CHF experiment with an annulus channel. The liquid sublayer dryout model was selected for the base mechanistic model. Since Lee & Mudawar [15] initially developed this model, numerous modified methods have been introduced or optimized for the coefficients used in the model. Among these, Liu [16] attempted to predict CHF in an annulus using the liquid sublayer dryout model, employing the Nouri liquid-phase velocity distribution correlation [17]. Based on Liu model [16], the mechanistic model for an annulus channel was established.

Using the established mechanistic model, validation calculations were performed against the static CHF data with an annulus channel from both the present experiment and previous studies [9, 18-20]. The comparison shows that most of the data fall within a ±20% error band (Fig. 4). As a result, the prediction capability of the established model for the static CHF of an annulus channel was validated. Detailed information on the calculation procedure and adopted sub-models can be found in the reference [9].

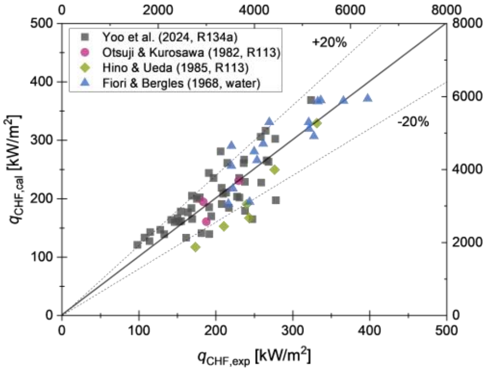


Fig. 4. Comparison results of calculated CHF with experimental data

2.4 Heaving CHF calculation results

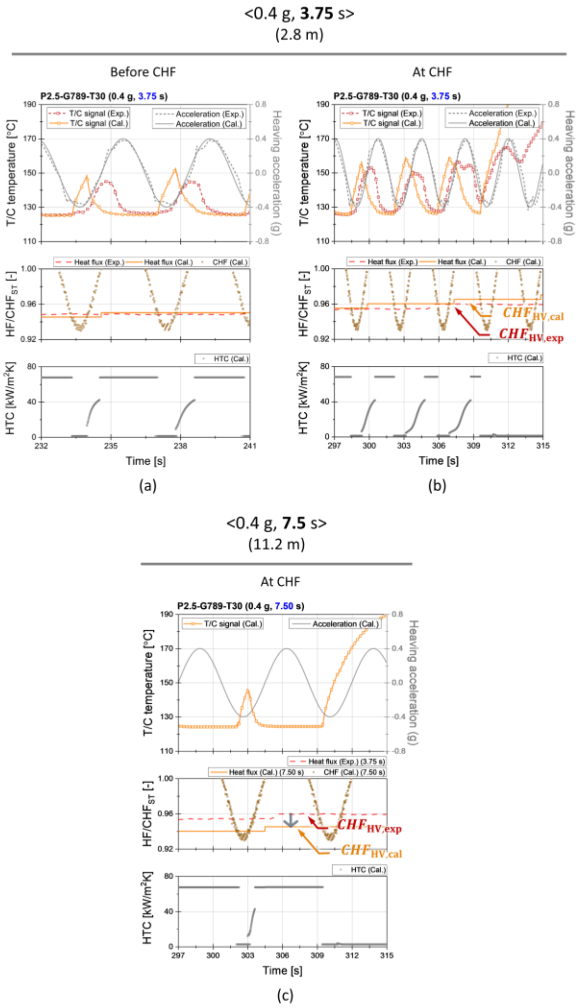
Using the developed methodology, a demonstration calculation was performed to estimate the period effect and fluid scaling effect on $\mathrm{CHF_{HV}}$. One of the experimental conditions from the previous study [7, 9] was selected as the reference case. The calculations with R134a were conducted for the heaving conditions tested in the experiment (0.4 g, 3.75 s) and for a longer period condition not tested in the experiment (0.4 g, 7.50 s) to analyze the period effect. In addition, the water equivalent condition of the reference case was simulated in order to analyze the fluid scaling effect. The water equivalent condition was determined based on the fluid-to-fluid scaling method [21]. The simulated conditions are detailed in Table I.

First, calculations were performed to examine the period effect for conditions where R134a is the working fluid, as shown in Fig. 5. For determining the heat transfer mode and calculating the transition boiling HTC with Eqs. 4 and 5, T_{MFB} and T_{CHF} were set to the observed experimental values of 130°C and 170°C, respectively. In Fig. 5-(a) and (b), comparisons were made between the experimental results and the calculation results. The upper graph shows the changes in the T/C signal due to heaving motion, the middle graph depicts the applied heat flux to the heater q''_{ext} and the instantaneous heaving CHF calculated through the mechanistic model as acceleration changes, and the lower graph presents the HTC calculated using Eqs. 2 – 5. In both the experiment and the simulation, a temperature rise of about 20°C to 30°C was observed under reduced gravity conditions with similar fluctuation amplitudes, and excursion occurred at comparable heat flux ratios. The temperature rise observed in the simulation appears slightly earlier than in the experiment, likely because the simulation does not account for the delay in bubble dynamics due to the external field.

Table I: Heaving conditions

Parameters	Reference	Period effect calculation	Fluid scaling effect calculation
Heater	Same (Monel K500 sheath and clad)		
Fluid	R134a	R134a	Water
Pressure	2.5 MPa	2.5 MPa	15 MPa
Mass flux	789 kg/m^{2}s	789 kg/m^{2}s	1097 kg/m^{2}s
Inlet subcooling	30 K	30 K	80 K
Acceleration magnitude	0.4 g		
Motion period	3.75 s	7.50 s	3.75 s
$\mathrm{CHF_{HV}/CHF_{ST}}$ (Calculated)	0.965	0.945	0.94 ~ 0.95

In the case of the 7.5 s period acceleration simulated in Fig. 5-(c), temperature excursion and CHF occurred at lower heat flux conditions compared to the experimental results of 3.75 s motion. This indicates that under a longer period acceleration field, CHF tends to occur earlier due to the extended duration of periodic dry patches, as reproduced by this simulation.



(a) (b)

(c)

Fig. 5. Calculation results on the period effect: (a) Before CHF in the short period case, (b) At CHF in the short period case, and (c) At CHF in the long period case

The calculation results for the water equivalent condition of the reference case are shown in Fig. 6. For T_{MFB}, Carbajo model [14] was used. T_{CHF} was determined under the conditions where the CHF obtained from mechanistic model equals the heat flux calculated by the nucleate boiling correlation. Meanwhile, the surface condition factor γ in Carbajo model has a value of 1 for a completely smooth surface, and the value increases as the surface becomes rougher. In most cases, γ is less than 10.0, so a range of 1.0 to 10.0 is recommended [14]. In this calculation, γ values of 1.0 and 10.0 were considered to correspond to the minimum and maximum possible T_{MFB} values. The calculated T_{MFB} values were 424 °C and 535 °C, respectively. As a result, the temperature rise rate was much faster compared to the case with R134a, and large temperature peaks and excursions were observed even with very short dry patch durations. This is because the temperature rise rate is influenced by the relationship between the applied heat in the heater and the heater's thermal capacity. When water is the working fluid, its latent heat is nearly ten times higher than that of the refrigerant, resulting in a higher CHF value. Therefore, a short duration of a dry patch can lead to the burnout of the heater due to the high-temperature rise rate. This result indicates that the temperature fluctuations observed prior to excursions under motion in the R134a experiment should not be generalized, as they depend on the specific fluid and heater thermal capacity used.

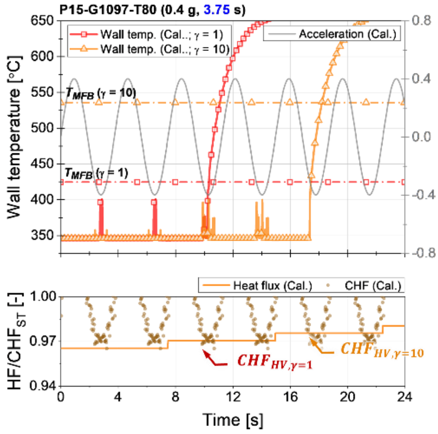


Fig. 6. Calculation results on the fluid scaling effect

3. Conclusions

A methodology for predicting CHF under heaving conditions was presented using a CHF mechanistic model. This methodology numerically analyzes the impact of changes in buoyancy and body forces due to heaving motion on void fraction, bubble size, and CHF triggering mechanisms through the force balance-based mechanistic model. The demonstration calculation reproduced the effects of motion period and fluid scaling hypothesized in the experimental analysis. It was confirmed that the periodic temperature fluctuations observed with simulant fluid could induce rapid and high-temperature rises in water experimental conditions, which could be identified as CHF. Therefore, these factors should be considered when analyzing the results of simulant fluid experiments and designing water experiments. Such analysis enhances the understanding of the mechanisms behind heaving CHF, and this phenomenological insight should be reflected in CHF prediction models under heaving motion.

For future work, visualization experiments, including the measurement of bubble behavior under motion conditions, can enhance the understanding of the motion effects on CHF. It can also provide phenomenological support for the CHF trigger mechanism in the mechanistic model. Furthermore, if it is confirmed that motion affects bubble parameters, improvements to the sub-models could enable the proposed mechanistic model-based methodology to provide a more accurate physical explanation of motion effects. Therefore, future work is recommended to involve visualizing two-phase flow and improving bubble sub-models for the primary parameters that significantly affect CHF prediction.

ACKNOWLEDGMENT

The content of this paper is based on the Ph.D. thesis of the first author. (Jin-Seong Yoo, Experimental investigation on critical heat flux of flow boiling in an annulus channel under heaving conditions, Ph.D. thesis, Seoul National University, Republic of Korea, 2024)

REFERENCES

[1] V. I. Kostin, Y. K. Panov, V. I.Polunichev, and I. E. Shamanin, Floating Power-Generating Unit with a KLT-40S Reactor System for Desalinating Sea Water. Atomic Energy, Vel.102, No.1, pp.31-35, 2007.

[2] Y. Bicer, and D. Ibrahim, Life Cycle Assessment of Nuclear-based Hydrogen and Ammonia Production Options: A Comparative Evaluation. International Journal of Hydrogen Energy, Vol.42, No.33, pp.21559-21570, 2017.

[3] J. S. Hwang, Y. G. Lee, and G. C. Park, Characteristics of Critical Heat Flux under Rolling Condition for Flow Boiling in Vertical Tube. Nuclear Engineering and Design, Vol.252, pp.153-162, 2012.

[4] G. W. Kim, J. S. Yoo, C. W. Lee, H. Hong, G. C. Park, and H. K. Cho, Critical Heat Flux Characteristics of Flow Boiling on a Heater Rod under Inclined and Rolling Conditions. International Journal of Heat and Mass Transfer, Vol.189, p.122670, 2022.

[5] G. W. Kim, J. S. Yoo, C. W. Lee, H. Hong, G. C. Park, and H. K. Cho, Critical Heat Flux Correlations for Tube and Annulus Geometries under Inclination and Rolling Conditions, Applied Thermal Engineering, Vol.225, p.120131, 2023.

[6] C. W. Lee, J. S. Yoo, H. Hong, H. Ko, J. H. Ku, G. W. Kim, and H. K. Cho, Experimental Investigation of Helical Fin and Inclination Effect on Critical Heat Flux, International Journal of Heat and Mass Transfer, Vol.215, p.124482, 2023.

[7] J. S. Yoo, C. W. Lee, H. Hong, H. Ko, J. H. Ku, G. W. Kim, and H. K. Cho, Experimental Study on Flow Boiling CHF in Annulus Channel under Heaving Conditions using Simulant Fluid R134a Targeting Nuclear Reactor Applications, Applied Thermal Engineering, Vol.236, p.121906, 2024.

[8] J. S. Yoo, C. W. Lee, H. Hong, H. Ko, J. H. Ku, G. W. Bae, and H. K. Cho, Experimental Study on Flow Boiling CHF of a Helical Finned Rod under Heaving Conditions using Simulant Fluid R134a, International Journal of Heat and Mass Transfer, Vol.232, p.125927, 2024.

[9] J. S. Yoo, Experimental Investigation on Critical Heat Flux of Flow Boiling in an Annulus Channel under Heaving Conditions, Ph.D. dissertation, Seoul National University, Republic of Korea, 2024.

[10] D. Steiner and J. Taborek, Flow Boiling Heat Transfer in Vertical Tubes Correlated by an Asymptotic Model, Heat Transfer Engineering, Vol.13, No.2, pp. 43-69, 1992.

[11] F. W. Dittus and L. M. K. Boelter, Heat Transfer in Automobile Radiators of the Tubular Type, Publication in Engineering, Vol.2, University of California, Berkeley, pp.443-461, 1930.

[12] V. Gnielinski, New Equations for Heat and Mass Transfer in Turbulent Pipe and Channel Flow, International Chemical Engineering, Vol.16, No.2, pp.359-367, 1976.

[13] T. A. Bjornard and P. Griffith, PWR Blowdown Heat Transfer, Thermal and Hydraulic Aspects of Nuclear Reactor Safety, Vol.I, 1977.

[14] J. J. Carbajo, A Study on the Rewetting Temperature, Nuclear Engineering and Design, Vol.84, No.1, pp.21-52, 1985.

[15] C. H. Lee and I. Mudawar, A Mechanistic Critical Heat Flux Model for Subcooled Flow Boiling based on Local Bulk Flow Conditions, International Journal of Multiphase Flow, Vol.14, No.6, pp.711-728, 1988.

[16] W. Liu, Prediction of Critical Heat Flux for Subcooled Flow Boiling in Annulus and Transient Surface Temperature Change at CHF, Fluids, Vol.7, No.7, p.230, 2022.

[17] J. M. Nouri, H. Umur, and J. H. Whitelaw, Flow of Newtonian and Non-Newtonian Fluids in Concentric and Eccentric Annuli, Journal of Fluid Mechanics, Vol.253, pp.617-641, 1993.

[18] M. P. Fiori and A. E. Bergles, Model of Critical Heat Flux in Subcooled Flow Boiling, Technical Report No. DSR 70281-56, Massachusetts Institute of Technology, 1968.

[19] T. Otsuji and A. Kurosawa, Critical Heat Flux of Forced Convection Boiling in an Oscillating Acceleration Field—I. General Trends, Nuclear Engineering and Design, Vol.71, No.1, pp.15-26, 1982.

[20] R. Hino and T. Ueda, Studies on Heat Transfer and Flow Characteristics in Subcooled Flow Boiling—Part 2. Flow Characteristics, International Journal of Multiphase Flow, Vol.11, No.3, pp.283-297, 1985.

[21] Y. Katto, A Generalized Correlation of Critical Heat Flux for the Forced Convection Boiling in Vertical Uniformly Heated Round Tubes, International Journal of Heat and Mass Transfer, Vol.21, No.12, pp.1527-1542, 1978.