Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2026

Measurements of critical heat flux in a 2x2 rod bundle under ocean conditions

Tan Hung Hoang, Byoung Jea Kim*
School of Mechanical Engineering, Chungnam National University, Daejeon, Republic of Korea
**Corresponding author: bjkim@cnu.ac.kr*

***Keywords:** Critical heat flux, rod bundles, fluid-to-fluid scaling, inclination, rolling.

1. Introduction

In recent years, floating nuclear power plants (FNPPs) have developed as an environmentally friendly solution for supplying energy to remote and island regions with limited access to power grids [1]. However, the dynamic motions induced by the marine environment can significantly alter the critical heat flux (CHF), which is the most important factor for the economic and safety of nuclear reactor operation. Therefore, several experimental and numerical studies related to CHF under marine motions have been conducted [2]. Recent studies on CHF experiments using a tube and a rod under rolling conditions [3, 4] have demonstrated that CHF may be enhanced and degraded compared to the vertical case, depending on the experimental conditions and heater geometry. Furthermore, empirical correlations for critical heat flux (CHF) in tubes and annuli subjected to rolling motion were proposed by Kim et al.[5], with a reported uncertainty of 9.5% at the 95% confidence level. However, the effect of the rod bundle on CHF under rolling conditions remains insufficient.

In this study, a CHF experiment on a 2x2 rod-bundle geometry with uniform power distribution under rolling conditions was conducted. The data obtained from the experiments can be used to validate and extend existing correlations, thereby enabling a more accurate representation of the unique flow characteristics of a rod bundle under ocean conditions.

2. Experiment works

2.1 Experiment facility

Fig.1 shown the CHF test loop was manufactured to circulate working fluid through the test section under various flow conditions. The experiment facility comprised a test section in which the CHF was measured, circulating pump, preheater, flow meter, condenser, and cooler. To control the pressure of the system, an accumulator is connected to a pump discharge nozzle. A preheater was used to control the temperature and the control valve was used to maintain the mass flow rate at the inlet of the test section. The condenser and cooler removed the heat of the system connected with the pump to make a close loop. The working fluid R134a was used for the CHF experiment instead of water, based on fluid–to–fluid scaling criteria for CHF, the CHF phenomenon can be preserved between two systems with different fluids. Instrument parameters such as mass flow rate, power, pressure gauges, inlet and outlet fluid temperature, wall temperature of heated rods, and rolling angle were collected during the experiments.

The test section was designed as a 2x2 rod bundle, as shown in Fig. 2. The heater rods of 9.5 mm diameter, 12.6 mm of rod pitch, and 1100 mm of total length were housed in a 28.3x28.3 mm square channel. The heated rod configuration was selected similar to typical PWR fuel assembly. Two simple grid spacers were installed at the top and bottom of the rods to maintain the spacing between the heated rods. The rod was uniformly heated along 700 mm of effective heated length by indirect heating DC power. The CHF could be detected at the end of the heated length. Therefore, the thermocouples are embedded in grooves at the end of the heated length to determine the boiling transition. The power should be increased step by step and wall temperature should be monitored for a sufficient time at each step. The CHF power is defined as the power corresponding to the step immediately preceding the step at which the wall temperature excursion does not return to an equilibrium state.

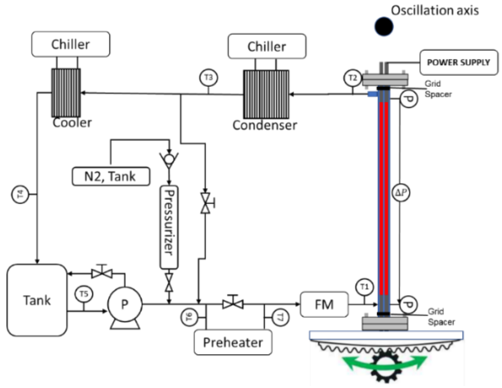

Fig.1 Schematic of the experiment setup

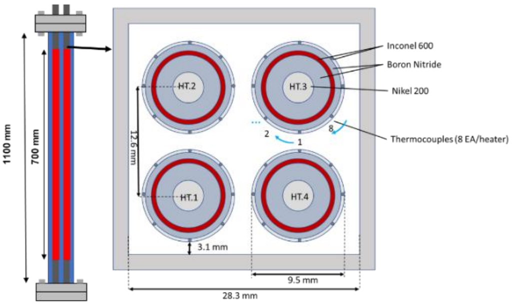

Fig.2 The cross-section view of test section

2.2 Experiment conditions

The experiments using R-134a as the working fluid to model the CHF characteristics of water due to its low latent heat, low critical pressure compared to water. Base on fluid-to-fluid scaling criteria for, experiment conditions and the corresponding water conditions are presented in Table 1. With each flow condition, vertical standing and three maximum amplitudes (θ_{max} = 5°, 10°, 15°) for both rolling and inclined states were considered. For rolling conditions two rolling periods (T = 6, 12 s) were perform with each rolling amplitude.

Table 1. CHF test conditions

Pressure (MPa)		Mass flux (R134a) kg/m^{2}s			
R134a	Water	140	400	820	1100
		Mass flux (Water) kg/m^{2}s			
1.1	6.84	200.5	572.8	1174.2	1575.2
2.0	11.95	197.3	563.6	1155.4	1549.9
3.0	17.10	193.6	553.2	1134.1	1521.3

3. Results and discussions

The preliminary results at a pressure of 11 bar, a mass flux of 140 kg/m²s, and subcooling temperature of 14 K are presented in Fig. 3. According to the criterion used in the study by Kim et al.[5] for identifying the CHF regime based on the Katto number $\psi_{Katto} = \sigma\rho_l/G^2 l_{heat}$, this condition falls within the CHF-Dryout region. In this region, the temperature increases gradually as the power rises until CHF occurs as shown in Fig 3 (a). The rolling cases at inclination angles of 5°, 10°, and 15° Fig. 3 (b), (c), and (d), CHF with precursors is observed. The CHF precursors exhibit periodic temperature oscillations. As the power is increased to a level close to the CHF condition, the surface temperature of the heater rods fluctuates more intensely and eventually rises continuously without returning to an equilibrium value. That point is recorded as the CHF value.

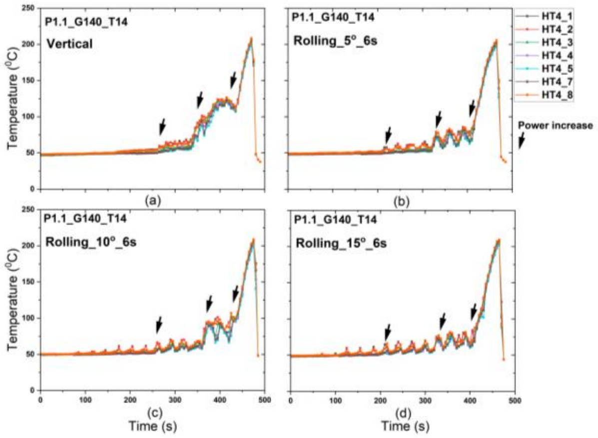

Fig.3 Wall thermocouple signal at CHF under vertical and rolling conditions

Fig.4 shows the CHF ratio between the inclined and rolling conditions compared to the vertical state. Under inclined conditions, the CHF value decreases compared to the vertical state. A similar reduction in CHF under inclination was also observed in the rod bundle experiments conducted by Isshiki [6]. This can be explained by the fact that under inclined conditions, the buoyancy force causes bubbles to migrate toward the downward-facing side of the test section. The bubbles then coalesce, which deteriorates the heat transfer from the heater rod and consequently reduces the CHF value.

On the other hand, CHF was slightly enhanced under rolling conditions because the vapor and liquid phases were continuously redistributed in a periodic manner, allowing the liquid phase to intermittently rewet and cool the heater rod. Nevertheless, in both cases, the observed variations remain within 5%.

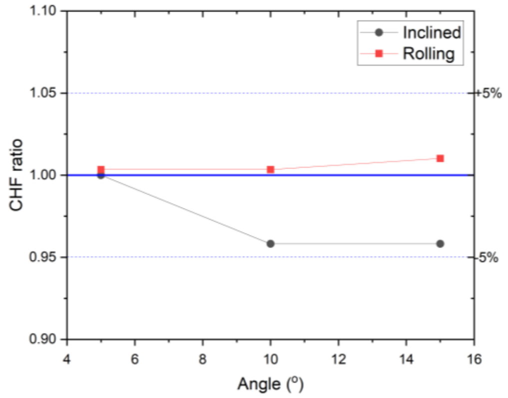

Fig.4 Effects of maximum amplitude on CHF under inclined and rolling conditions

4. Conclusions

In this study, CHF experiments were performed using a 2 × 2 rod bundle to examine the effects of ocean conditions on CHF. Rolling conditions introduce CHF precursors characterized by periodic wall temperature fluctuations, while no such fluctuations are observed under vertical conditions. Inclined and rolling motions have opposite but limited effects on CHF: CHF decreases under inclined conditions and slightly increases under rolling conditions, with variations remaining within 5%. Further work involves conducting experiments under different operating conditions to clarify the effects of marine motion on the CHF value and to validate the existing CHF prediction models.

5. Acknowledgements

This work was supported by grants from the National Research Foundation of Korea, funded by the Ministry of Science and ICT (No. RS-2024-00393526 and 2021M2D2A1A02039565).

6. References

[1] IAEA, "Small Modular Reactors for Marine-Based Nuclear Power Plants," 2023.

[2] Z. Tian, B. Gu, Y. Zhang, and W. Gao, "Flow boiling heat transfer under marine motions: A comprehensive review," *Annals of Nuclear Energy*, vol. 143, 2020, doi:10.1016/j.anucene.2020.107455.

[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, doi: 10.1016/j.nucengdes.2012.06.032.

[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, 2022, doi: 10.1016/j.ijheatmasstransfer.2022.122670.

[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, 2023, doi: 10.1016/j.applthermaleng.2023.120131.

[6] N. Isshiki, " Effect of heaving and listing upon thermo-hydraulic performance and critical heat flux of water-cooler marine reactors," *Nuclear Engineering and Design*, 1966.