Experimental Observation of Heaving Motion Effect on CHF in Helical Finned Rod with Working Fluid of R134a

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1. Introduction

Offshore nuclear reactor can broaden the application of Small Modular Reactors (SMRs) to ocean environments, serving as sources of seawater desalination or providing electricity and process heat to regions with limited access to conventional power grids, such as islands and coastal regions [1]. However, since these systems are operated in marine conditions, it is crucial to assess the effect of changes in pressure head and external forces, which is arising from marine conditions, on the safety of the system. Specifically, their effect on the Critical Heat Flux (CHF) should be elucidated because CHF is one of the important parameters in determining reactor core power and thermal safety margins. However, the experimental research on this realm remains insufficient, and thus, Seoul National University has been conducting experimental studies to investigate the effect of ocean conditions on CHF, and especially, CHF of a helical finned rod under the rolling condition has been studied [2, 3].

Helical finned rods are expected to have high thermal performance, such as a large heat transfer area to volume ratio and swirling flow by fins, so studies are being conducted to use them in existing commercial nuclear power plants. In addition, this type of fuel rods has the advantage of being self-supporting and thus enduring well against external shock and vibration without a support grid [4]. Accordingly, Russia has adopted a similar geometry of three-petal fuel rod for marine nuclear reactor [5, 6].

In this experiment, the CHF of a helical finned rod under heaving motion was studied experimentally. The parametric trend of the heaving motion effect was confirmed, thereby elucidating the distinct changes of the CHF on a helical finned rod.

2. Experimental facility

2.1. Heaving motion platform, NEOUL-H

NEOUL-H is a platform that can simulate the heaving motion of the ocean environment. The main motion parameters are the acceleration magnitude and period. When the heaving motion is given by Eq. (1), the theoretical value of heaving acceleration can be calculated by Eq. (2).

(1) $A(t) = A_m \sin\left(\frac{2\pi}{T}t\right)$

(2) $a(t) = -A_m \frac{4\pi^2}{T^2} \sin\left(\frac{2\pi}{T}t\right)$

where A, A_m, T and a are the displacement of the test loop, amplitude of heaving motion, heaving period, and heaving acceleration, respectively. The platform was designed to simulate acceleration of up to 0.6 g and a cycle period of 3 seconds based on the ocean data in the open literature [7, 8].

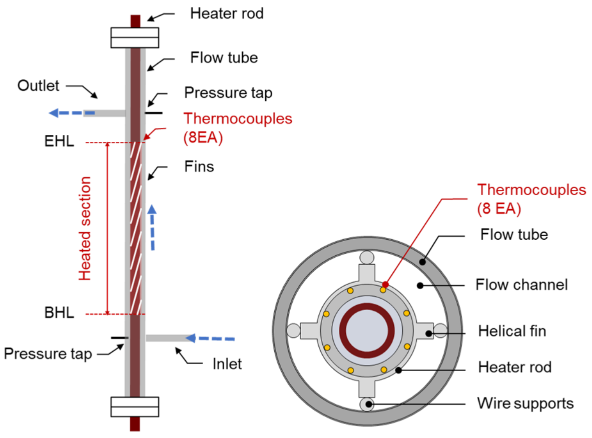
In this experiment, both static and heaving tests were performed for each thermal-hydraulic test condition to confirm the heaving motion effect. The tested motion conditions can be found in Table I. The term "stroke" corresponds to the distance covered by the test loop due to the platform's motion in a single cycle.

Table I: Heaving conditions

Acceleration magnitude [g]	Stroke [mm]	Period [s]
0.2	2800	5.31
	1400	3.75
	900	3.01
0.4	2800	3.75
	1800	3.01
0.6	2800	3.06

2.2. Test section and test conditions

As depicted in Fig. 1, the test section has an annulus geometry with upward fluid flow. The tests were conducted under PWR operating pressure conditions using the simulant fluid R134a, based on the fluid-to-fluid scaling method [2]. A heater, wrapped by four fins spiraling counterclockwise, was used to investigate the effect of helical fins on CHF. Each fin wraps around the heating surface twice, spanning from the Beginning of Heated Length (BHL) to the End of Heated Length (EHL). Due to the uniform axial heating of the heater rod, CHF is anticipated to occur at the EHL. Hence, to detect the CHF occurrence, eight thermocouples were evenly placed around the four fins at EHL. Furthermore, four linear wire supports were employed for the concentric annulus channel. The power input was increased stepwise by less than 1% until CHF occurs, and subsequently reduced upon observing a sudden rise in wall temperature. Throughout the heaving experiment, the thermal-hydraulic condition, such as the inlet temperature, outlet pressure, and mass flux were maintained in a nearly consistent value, and a summary of the test conditions can be found in Table II.



(a) (b)

Fig. 1. Schematics of test section
(a: side view, b: cross-sectional view)

Table II: CHF test conditions

	Test conditions (R134a)	Water equivalent conditions
Outlet pressure [MPa]	1.6 ~ 3.2	10 ~ 18
Mass flux [kg/m^{2}s]	100 ~ 2200	150 ~ 3000
Inlet subcooling [K]	8 ~ 43	21 ~ 117

3. Experimental results

The CHF in static and heaving conditions is defined as the heat flux at which an excursion in wall temperature occurs and the excursion persists until the power is cut off. Under static conditions, the geometry effect by fin was confirmed through comparison with bare rod test results. In heaving motion conditions, parametric study on the motion effect was performed.

3.1. Static condition

As shown in Fig. 2, the critical power of the bare rod and the helical finned rod are compared according to critical quality. It could be confirmed that the helical finned rod has a higher critical power than the bare rod at the same critical quality, suggesting that the CHF occurrence is delayed due to the geometric effect. This increasing tendency was observed throughout the experimental results regardless of the critical quality, and this can be explained by the following hypothesis [3]: for the dryout case with annular flow, the swirl flow by four fins enhances the extraction of droplet from the dense liquid film on the fin surface and flow tube wall, where the temperature remains comparatively lower. These droplets are then deposited at the base of the fin, where the dryout occurrence is primarily anticipated. In the DNB cases with bubbly flow, the bubbles tend to detach easily from the heated surface due to collisions with the fin structure. Consequently, this leads to the increase in critical power.

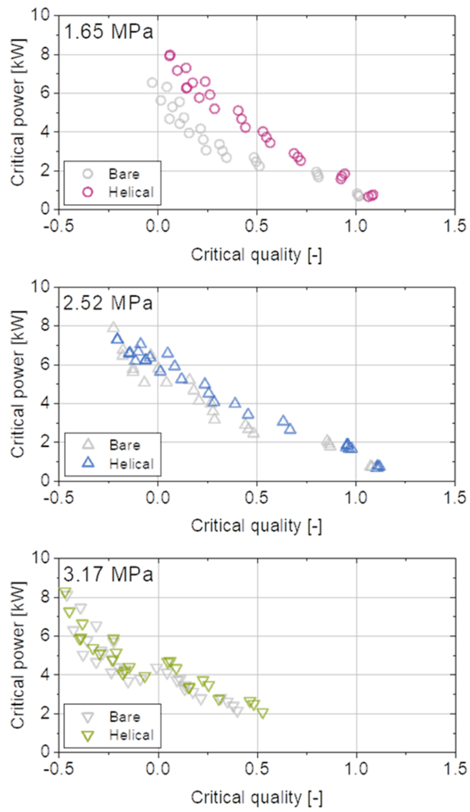


Fig. 2. CHF of bare and helical finned rod according to critical quality by pressure

3.2. Heaving condition

The parametric trend for heaving motion effect was confirmed through Fig. 3 and Fig. 4. At each graph, the y-axis represents the heaving motion effect as the CHF ratio between the static case and the heaving case. If the y value is greater than 1, it means that CHF was increased due to the heaving motion, and if the y value is less than 1, it means that CHF was decreased due to the heaving motion. Overall, CHF change due to the motion was observed to be within 5%. The observed parametric trend exhibited intricate characteristics, though a shared observation was that a higher magnitude of acceleration corresponded to greater rates of CHF variation. Furthermore, within each graph, distinct features highlighted in yellow, blue, and red were identified.

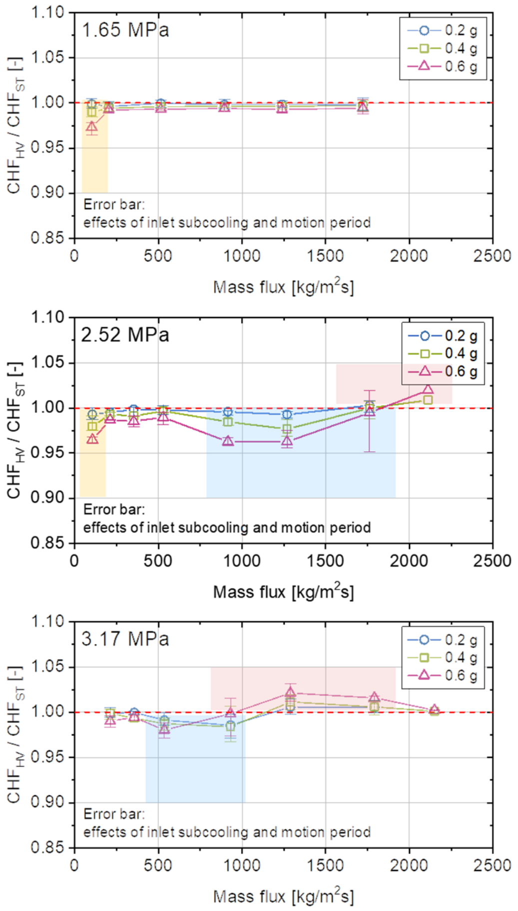


Fig. 3. Parametric effect of heaving motion on CHF: mass flux

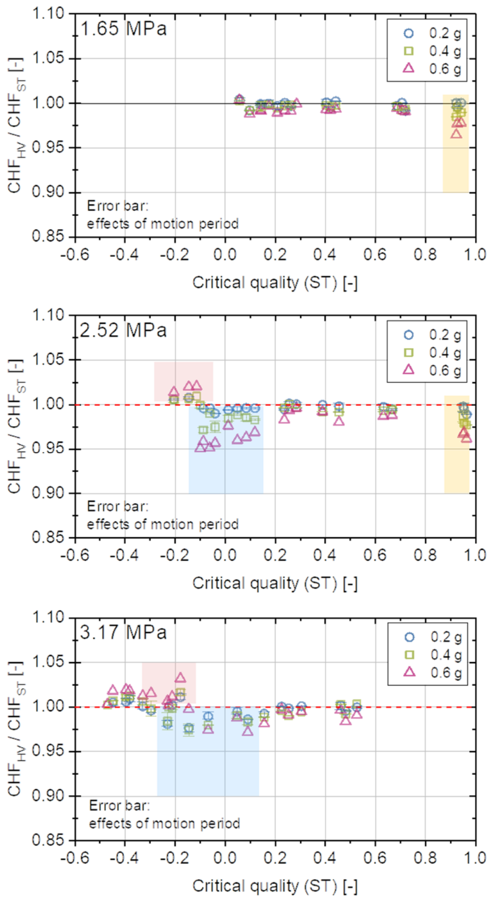


Fig. 4. Parametric effect of heaving motion on CHF: critical quality

As shown yellow and blue region in Fig. 3 and Fig. 4, CHF decreased due to the heaving motion, which is the region where the critical quality is higher than 0.8 and the region where the critical quality is near 0. This tendency was commonly observed in experiments with bare rod, and it has been confirmed that the main cause is the decrease in net gravity due to the motion [9]. For the yellow area of annular flow, the decreased gravitational force on liquid film can incur the thin liquid film thickness, leading to the early occurrence of dry patch. For the blue area of bubbly flow, the decrease in buoyancy contributes to a decrease in the relative velocity between phases, resulting in a higher vapor fraction. This phenomenon, in turn, fosters the early occurrence of CHF. Finally, as indicated in the red area, an increase in CHF was observed around the critical quality of -0.2. This CHF enhancement has not been observed in the bare rod test, and it is thought that the periodic increase and decrease in buoyancy causes the bubble to collide with the fin structure, which increases the CHF by suppressing the generation of large bubbles. Nevertheless, in cases where the mass flux is high enough, the fluid inertia surpasses the heaving motion effect, and the motion effect diminishes.

4. Conclusion

In this study, the CHF measurement experiment was performed on a helical finned rod under heaving conditions. An R134a CHF test loop was constructed on the platform to determine the effect of heaving motion on the CHF phenomenon. The separate effect of cyclic heaving acceleration could be observed through the present experiment, and it was confirmed that the heaving motion led to periodic increase and decrease in CHF depending on thermal-hydraulic conditions. Furthermore, the parametric effect of heaving motion on CHF was investigated. The change in the CHF due to the heaving motion was within 5%, but the heaving effect was prominent at three regions: CHF decreased near 0 and above 0.8 of critical quality, CHF increased near -0.2 of critical quality. The first two characteristics of CHF decrease have been observed in previous studies using bare rods, but the increase in CHF is thought to be due to the effect of the helical finned geometry. In the heaving condition, especially with the current geometric configuration, there is no applicable correlation for CHF prediction. Consequently, the experimental observations of this study can be utilized for the evaluation of the thermal safety margin of offshore nuclear power plants.

In order to elucidate the CHF variation mechanism, experimental results are under analysis based on the wall temperature response during heaving motion.

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