# A Parametric Study on Pool Boiling CHF Phenomenon in Heaving Conditions: The Effects of Heaving Periods

Do Yeon Kim, Su Cheong Park, Seonho Choi, Dong In Yu *
*Department of Mechanical Design Engineering, Pukyong National Univ.,45, Yongso-ro, Nam-gu, Busan 48513*
**Corresponding author:diyu@pknu.ac.kr*

## 1. Introduction

Currently, the domestic shipbuilding industry is focusing on nuclear power projects such as small module reactors (SMR). SMR, which is used for floating marine nuclear power, has a wide range of applications, and the market size of the business is increasing. In addition, in order to realize greenhouse gas reduction and carbon neutrality, the need for nuclear power, which is an eco-friendly energy in terms of greenhouse gas emissions, is increasing. Therefore, research and development on floating marine nuclear power that can stably supply electricity to marine resources or island areas where it is difficult to construct power plants is in progress.

In the case of floating marine nuclear power plant, unlike ground nuclear power plant, it is affected by ocean motion and affects the thermal hydraulic phenomenon in the nuclear power plant such as boiling heat transfer and critical heat flux (CHF). There are 3 types of linear motion and 3 types of rotational motion in ocean motion, and among the 6 types, roll, pitch, and heave affect gravity. Acceleration is determined by two variables, length and period. Experiments are being conducted to understand the thermal hydraulic phenomenon during ocean motion according to the variables.

According to a previous study by Zuber [1], the gravitational acceleration affects CHF, which is a major factor in thermal hydraulic design. It has been reported that CHF decreases as gravity decreases. Otsuji et al.[2] reported that CHF decreased in proportion to the 1/4 square of the minimum gravity under heave conditions, and Isshiki [3] reported that it decreased linearly proportional to the minimum gravity under heave conditions. The two previous studies showed different CHF reduction trends.

In this study, in order to understand the thermal-hydraulic phenomenon in heaving conditions during ocean motions, a heaving platform that simulates the marine environment is designed and manufactured. The pool boiling experiments have conducted in the conditions; the fixed amplitude and various periods. Comparing of experimental data between stationary and heaving conditions, we have checked the period effects of thermal hydraulic phenomena in pool boiling.

## 2. Experimental setup

### *2.1 Heaving platform*

In this study, a pool boiling experiment was conducted by manufacturing a platform that moves up and down. In order to simulate the severe ocean motions, the up-and-down fluctuation platform was designed to meet the conditions of 0.45g of acceleration, 1 m of amplitude, and 3 sec of period, which are observed at Dokdo in May or June Island during typhoon. To prevent the fatigue load on the platform, it was driven for 4 minutes and rested for 3 minutes. The platform controls the vertical motion of the platform using the rotational amount of the four servo motors. A wire sensor was attached to measure the motion of the platform. As shown in Figure 2, it was confirmed that the motion of the platform satisfies the sin waveform and 0.45g acceleration.

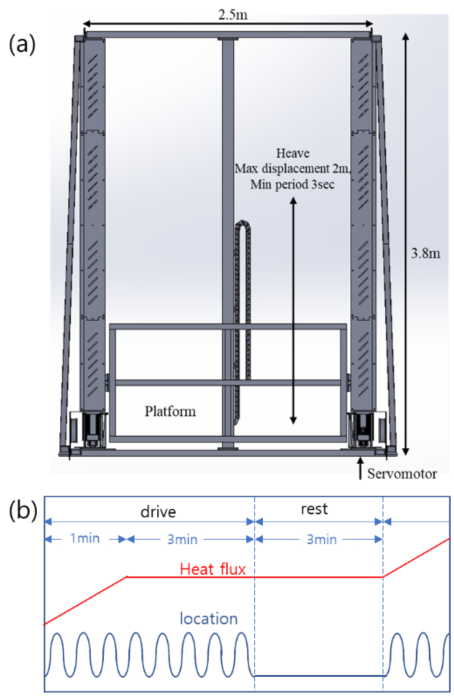


Fig. 1. (a)Heaving platform, (b) Platform drive mode

The acceleration of the sin waveform by heaving motion platform is expressed as the following equation.

$$a(t) = -A_m \left(\frac{2\pi}{T}\right)^2 sin\left(\frac{2\pi}{T}t\right) \quad (1)$$

$$a_h = A_m \left(\frac{2\pi}{T}\right)^2 / g \quad (2)$$

$T$ is the period, $A_m$ is the amplitude, $a$ is the acceleration generated by the platform and $a_h$ is the maximum heaving acceleration rate by the platform. The acceleration generated by the motion of the platform is determined by two variables, amplitude and period, as shown in Equation (1).

In order to understand the pool boiling phenomenon under heaving conditions, an experiment was conducted by fixing it to an amplitude of 1 m (namely, the maximum displacement is 2m) and changing the period to 3-6.7 sec. The experimental conditions are shown in Table 1.

Table I: Heaving motion test condition

| Case | $A_m$ [m] | $T$ [s] | $a_h$ [-] | $g(1- a_h)$[m/s$^2$] |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1g |
| 2 | 1 | 6.7 | 0.09 | 0.91g |
| 3 | 1 | 4.7 | 0.18 | 0.82g |
| 4 | 1 | 3.9 | 0.27 | 0.73g |
| 5 | 1 | 3.4 | 0.36 | 0.64g |
| 6 | 1 | 3 | 0.45 | 0.54g |

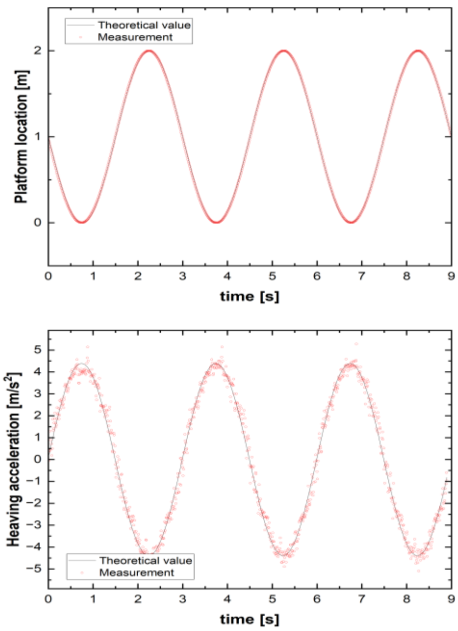


Fig. 2. Theoretical values and measurements of platform location, acceleration

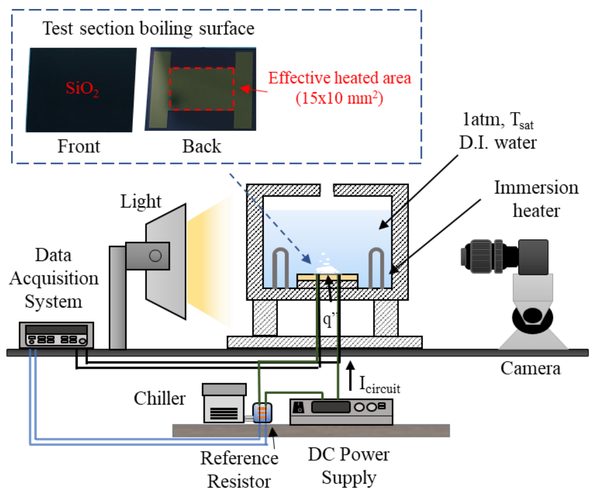


Fig. 3. Pool boiling apparatus

*2.2 Pool boiling setup*

The pool boiling experimental apparatus as shown in fig 3 is placed inside the platform. The test sections were prepared by depositing a 5000Å oxide layer on a silicon wafer and depositing a platinum thin film heater on the back side. The test section and the reference resistance were connected in series and a voltage was applied through a DC power source. The voltage was measured by cDAQ-9178. Heat flux was calculated by measuring the voltage applied across the test section. And, the platinum thin film heater of test sections has linear relations between wall temperature and electrical resistance. Before pool boiling experiments, we had obtained the linear relations by calibration processes. The wall temperature had obtained by measuring the electrical resistances. At this time, the obtained data are the wall temperatures of bottom sides. And, the platinum thin film heater of test sections has linear relations between wall temperature and electrical resistance. Before pool boiling experiments, we had obtained the linear relations by calibration processes. The wall temperature has obtained by measuring electrical resistance. At this time, the obtained data are the wall temperatures of bottom sides. Therefore, we had calculated the wall temperature of inner pool sides with assuming one direction heat conduction. The pool boiling experiment was conducted with distilled water at atmospheric pressure and saturated conditions.

## 3. Results

*3.1 CHF Occurrence location*

In order to understand the thermal hydraulic phenomena in ocean motion, pool boiling experiments were conducted under heaving conditions. First, the occurrence of CHF with a rapidly in wall temperature was observed. CHF is a phenomenon in which the boiling region changes from the nucleate boiling region to the film boiling region, and the wall temperature rises rapidly. Fig. 4 shows the location and wall temperature of the platform over time in the section before and after the CHF phenomenon occurs. As shown in Fig. 4, it was observed that the temperature rapidly increased when the platform performing the periodic heaving condition was located near the top. Acceleration changes periodically depending on the location of the platform in heaving condition, and when it is located at the top, the acceleration ($g(1$-$a_h)$) acting on the platform is the minimum. Therefore, it can be seen that CHF occurs at a point where the acceleration acting on the heaving platform ($g(1$-$a_h)$) is minimized.

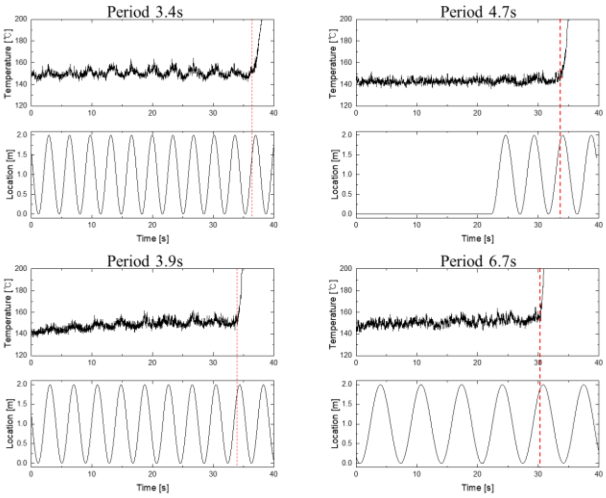


Fig. 4. Temperature over time, platform position

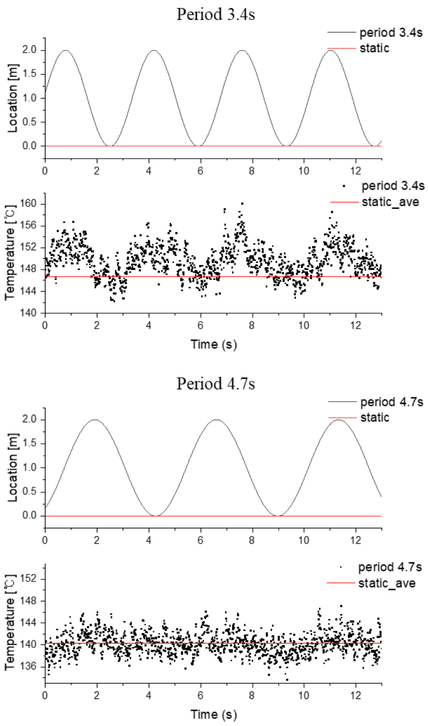


Fig. 5. Comparison of temperatures in static and heaving conditions at heat flux 900 kW/m$^2$

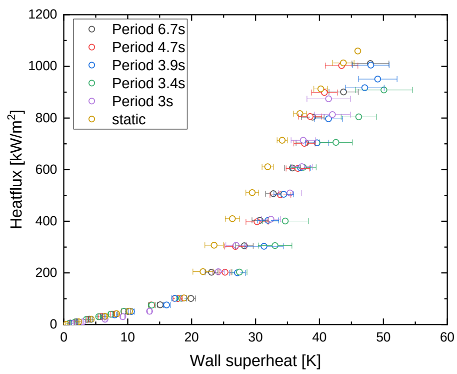


Fig. 6. Boiling curve in various heaving period conditions

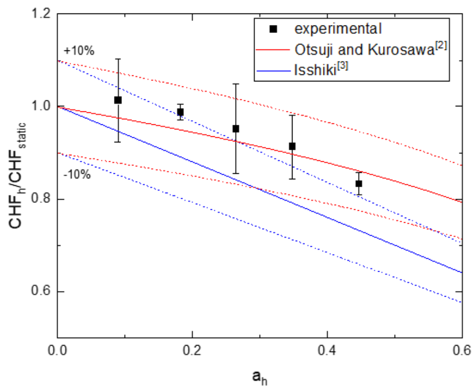


Fig. 7. CHF ratio according to maximum heaving acceleration rate [-]

### *3.2 Experimental results according to period*

When the wall temperature was measured over time in the heaving condition, the wall temperature change was confirmed with the same period as the heaving condition. The width of the changing temperature increased as the period became shorter. The wall temperature of the sample was measured to be high when the platform was located at the top, and the wall temperature was measured to be low when the platform was located at the bottom. [Fig. 5]

Fig. 6 shows the boiling curve, which is the heat flux according to the degree of superheat. Unlike the static condition, the boiling curve under the high heat flux condition is located on the right side, and it could be verified that the heat transfer coefficient decreases under the high heat flux condition.

Fig. 7 shows the CHF ratio according to the acceleration caused by the heaving condition. The predicted values of Otsuji and Kurosawa [2] and Isshiki [3] and the experimental values of this study were shown. The CHF average value in the stationary condition was, 1023 ± 76 kW/m$^2$. In previous research, Otsuji and Kurosawa [2] reported that the CHF value gradually decreases as heaving acceleration increases. However, Isshiki [3] insisted that the CHF value linearly decreases as heaving acceleration increases. On the fixed heaving amplitude, decreased having period means increased heaving acceleration. As shown in Fig. 7, at the results of these experiments, the CHF value gradually decreases as heaving period decreases. And, it is closed to the predicted value of Otsuji and Kurosawa [2] than the value of Isshiki [3].

A previous study, Haramura and Katto [4], postulated the existence of a macrolayer between the heated surface and the mushroom bubbles. According to their CHF model, the CHF occurs when the liquid does not flow into the macrolayer and the layer completely evaporate during hovering period of mushroom bubble. On the basis of the model, the heaving effect would be elucidated as follows. As heaving period (T) decreases (gravitational acceleration ($g(1-a_h)$)) deceases), hovering times of mushroom bubbles could decrease. And the reduced gravitational force for mushroom bubble would disturb bubbles from escaping from the heated surface. The CHF would occur at a relatively low heat flux due to the increased hovering period. For the reasons, the CHF would decrease, as the heaving period decreases as like our experimental data.

## 3. Conclusions

This experimental study is to understand the thermal hydraulic phenomenon in pool boiling under ocean motions. In order to simulate the heaving conditions among ocean motion, a heaving platform was designed and manufactured. The heaving platform is driven by satisfying a maximum acceleration of 0.45g and a minimum period of 3 sec. Most CHF occurs when the platform is located near the top, and it can be seen that CHF occurs at the point where the acceleration acting on the platform ($g(1\text{-}a_h)$) is minimized. It was confirmed that as the heaving period decreases, the change in wall temperature of the surface increases and the heat transfer decreases. In the various heaving period conditions, as maximum heaving acceleration increases, CHF gradually decreases and tends to be close to of Otsuji and Kurosawa's estimations.

In this study, the pool boiling test was conducted under various heaving period conditions among the two variables that determine acceleration. In further study, the results of each variable will be compared and analyzed to identify the thermal hydraulic phenomenon according to acceleration. To understand the interaction between steam columns under heaving conditions, the pool boiling experiments will be conducted with test sections of the size of 10x70 mm$^2$. (In this study, the size of test sections is 10 x15 mm$^2$.)

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