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An Experimental Study on Pool Boiling CHF Phenomenon in Heaving Conditions

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1. Introduction

Floating offshore nuclear power plant is a nuclear power generation method that can efficiently supply power to island regions where infrastructure is lacking and transmission lines are difficult to install. Russia is operating the first floating nuclear power plant ' Akademik Lomonosov' and is developing it not only in Korea, but also abroad, such as the United States and China, according to the need for offshore nuclear power generation systems.

Unlike large-scale nuclear power plants on the ground that are fixed on the ground and do not move, floating offshore nuclear power plants are affected by the marine environment and perform three straight movements and three rotational movements like ships. The movement of these floating nuclear power plants affects the thermal-hydraulic phenomenon in the nuclear power plant.

In particular, according to Zuber's correlation equation, studies have been reported that the critical heat flux (CHF), which is a major thermal hydraulic design factor, is affected by gravity.

$$q''_{CHF} = 0.131 h_{lg} \rho_g^{0.5} [\sigma g (\rho_l - \rho_g)]^{1/4} \quad (1)$$

Among the motions of floating nuclear power plants, the motions that affect gravity are Heave, Roll, and Pitch. This research team is conducting a study to analyze the effect of vertical fluctuations on the thermal hydraulic phenomenon among the three movements.

As a result of the analysis of previous studies on the effect of vertical fluctuations on the thermal hydraulic phenomenon, the critical heat flux value decreases as the minimum gravity caused by vertical fluctuations decreases, but a conflicting trend has been reported. Isshiki[2] reported that the critical heat flux value decreases in a linear trend according to the minimum gravity acting by the vertical fluctuation, but Ostuji and Kurosawa [3] reported that the critical heat flux value was proportional to the 1/4 square of the minimum gravity and reported to decrease.

In order to verify and analyze the effect of vertical swing on the thermal hydraulic phenomenon, this research team manufactured a vertical swing platform with a maximum wave height of 2 m and a minimum period of 3 seconds at the maximum wave height to realize vertical swing at sea. In order to analyze the effect on the thermal hydraulic phenomena, we install experimental apparatus on the vertical movement platform and conduct pool boiling experiments with the device and the platform.

In this study, for the verification of the pool boiling experimental apparatus and the heaving platform, the results of the change of the critical heat flux due to the heaving motion are checked by comparing the results of the pool boiling experiment in the stationary state and the heaving period of 3 seconds.

2. experimental setup

2.1 Heaving platform

Fig.1 is platform's shape. the platform 4 axis servo motor using are manipulating. In order to imitate the heaving motion, the platform is driven with a sine wave with a maximum displacement of 2 m, an amplitude of 1m, and a minimum period of 3 sec. It can be expressed as the following formula, and the minimum gravitational acceleration at this time is 0.44 g.

$$L(\mathrm{t}) = A_m \sin\left(\frac{2\pi}{T} t\right) \quad (2)$$

$$V(t) = A_m \frac{2\pi}{T} \cos\left(\frac{2\pi}{T} t\right) \quad (3)$$

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

A_m [m] is the amplitude of heaving motion, T [s] is the heaving period, and a [m/s^2] is the heaving acceleration.

The safety-significant wave height in marine conditions is on average 1 m in the case of the west coast, with a period of 3-7 sec, and the significant wave height in the east coast is 2 m. To represent the heaving motion, a gyroscope sensor with a time resolution of 10 Hz and an acceleration resolution of 0.005 g was used.

2.2 Pool boiling experimental setup

The pool boiling experiment apparatus was configured as in Fig.2. At atmospheric pressure, it was saturated, and the working fluid was deionized (D.I.) water. The test sections were the polished SiO_2 wafer, and a platinum thin film heater was fabricated on the backside with MEMS techniques. The temperature and heat flux of the test sections were calculated using the applied voltage by connecting, DC power supply, and standard resistor in series. The heaving motion test conditions are shown in Table 1. The period was fixed at 3 sec, and the experiment was conducted with various gravitational accelerations by changing the amplitude. Fig.3 is a

Table I: Heaving motion test condition

Amplitude [m]	Period [s]	Acceleration [-]
0	0	0
0.25	3	0.11
0.85	3	0.38
1	3	0.44

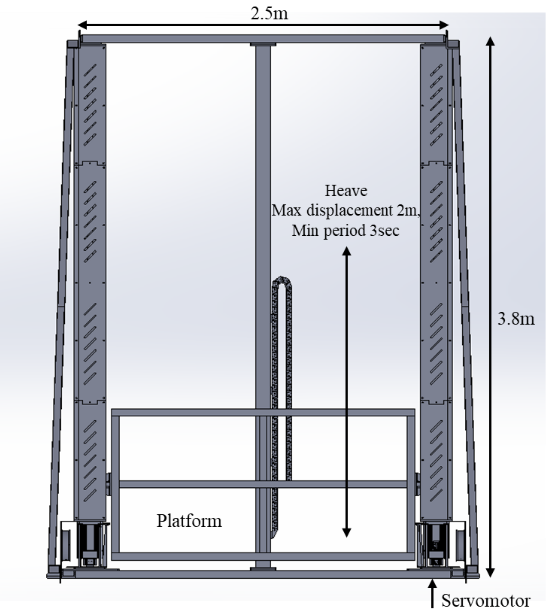


Fig.1. Heaving platform

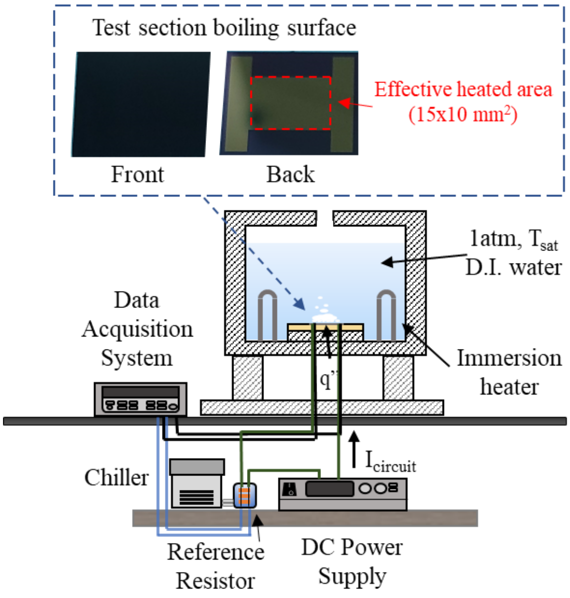


Fig.2. Schematic diagram of pool boiling experimental apparatus

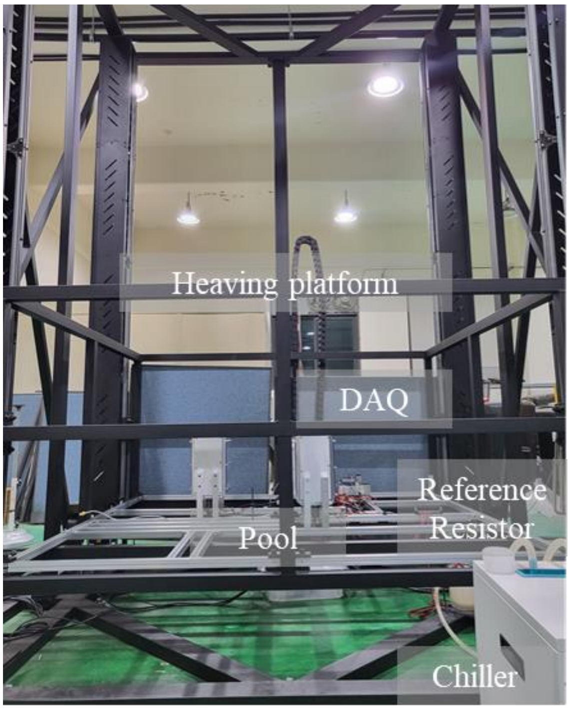


Fig.3. The image of pool boiling experimental setup in heaving platform

picture of the pool boiling experiment device installed on the actual platform.

3.results

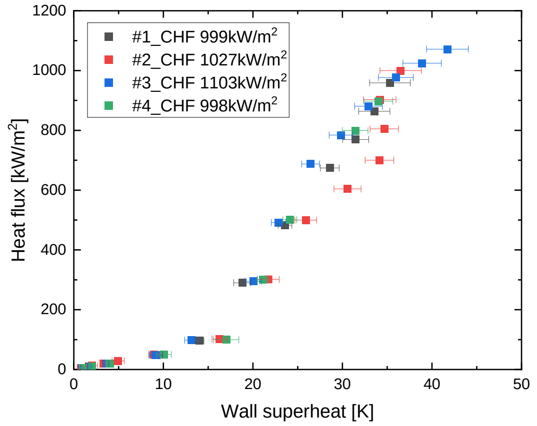
3.1 CHF in static condition

Fig.4(a) shows the result of the pool boiling experiment under static condition as a boiling curve, which is the heat flux according to the wall superheat. To check the reproducibility, repeated experiments were performed 4 times, and the boiling curves have a similar tendency as a result of the experiment. The measured CHF average is 1030 kW/m^2.

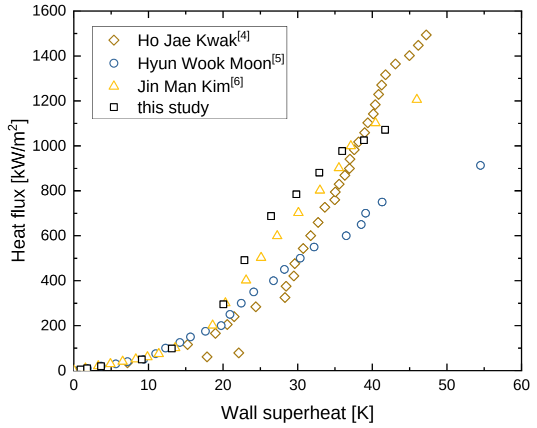
Fig.4(b) is the experimental data of SiO_2 of other previous studies[4-6]. The experimental data results of the previous study were compared with the experimental results of this study, it was confirmed that they had a similar graph shape. Through this, the pool boiling test apparatus was verified, and the experiment was performed under heaving condition using the pool apparatus.

3.2 Verification of acceleration in heaving condition

Heaving platform is an experimental device that implements vertical movement and satisfies the conditions of maximum amplitude of 1 m and minimum period of 3 sec. The vertical motion is driven by a sinusoidal waveform, and it was confirmed that an ideal sinusoidal waveform appears when the rotation amount of the servomotor is measured. To represent the actual operation of the lifting platform, a gyroscope sensor was attached to the device and motion was measured.



(a)



(b)

Fig. 4. Boiling curves under static conditions (a) Experimental data for this study (b) The previous research data

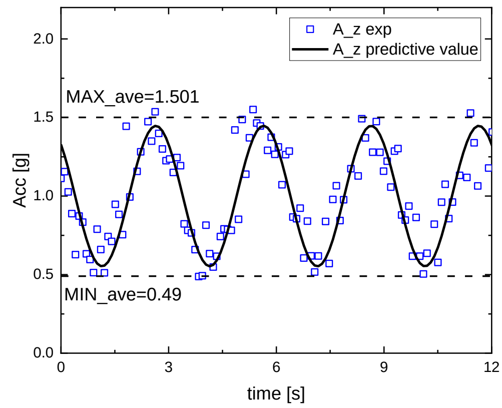


Fig.5. Comparison of acceleration between experimental and predictive value

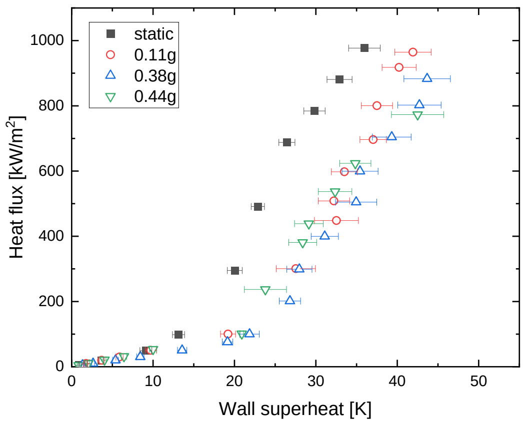


Fig. 6. Boiling curve in heaving condition

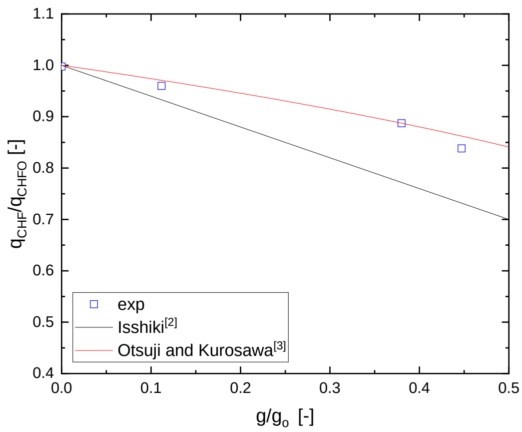


Fig.7. Comparison between the predictive and the measured CHF ration values in heaving motion

Fig.5 is a graph showing the acceleration and predictive values in the z-axis direction over time measured by the sensor under heaving condition. The measured x-axis acceleration ratio is 0.009 and the y-axis acceleration ratio is 0.01. The sensor's acceleration resolution is 0.005 g, and it is judged that there is little effect of the x and y-axis acceleration as a measurement error of the sensor.

The graph shape of the measured z-axis acceleration ratio was sinusoidal, and it was confirmed that the heaving device was operated as designed. Compared with the graph of the acceleration value measured by the sensor and the predictive value were compared, it was showed similarly. The maximum predictive acceleration ratio is 1.447 and the minimum is 0.552.

The average of the measured maximum acceleration ratio is 1.501, and the error from the predictive value is 3.7 %. The average of the measured minimum acceleration ratios is 0.49, and the error from the predictive value is 11 %. The heaving platform acceleration ratio is data measured by a gyroscope sensor with a time resolution of 10 Hz. In the future, a laser sensor with a time resolution of 100 Hz will be attached and the acceleration will be precisely measured and the experiment will be carried out.

Fig.6 is the boiling curve obtained by conducting the pool boiling experiment under heaving conditions. Comparing the boiling curves under static and heaving conditions, it can be seen that there is no difference in the heat transfer coefficients in the natural convection region. At nucleate boiling regions, the heat transfer coefficient is lower at heaving conditions than the static condition.

Fig.7 shows the measured CHF value according to the minimum acceleration due to the heaving motion and the CHF trend reported in previous studies. As the gravitational acceleration decreases, it can be seen that the CHF tendency also decreases.

Equation (5) shows the results of Isshiki[2], a previous study of CHF trend according to acceleration.

$$\frac{q_{CHF}}{q_{CHFO}} = 1 - 0.6\frac{\triangle g}{g_o} \qquad (5)$$

The ratio of the acceleration is proportional to the CHF ratio. The result of Otsuji and Kurosawa [3] is expressed in Equation (6).

$$q_{CHF} / q_{CHFO} = (1 - \mathrm{a}/ \mathrm{g}_o)^{1/4} \qquad (6)$$

q_{CHF} is CHF of heaving condition, and q_{CHFO} is CHF of stationary state. a is the acceleration and g_o is the gravitational acceleration of 9.81 m/sec^2. Therefore, it was verified that the experimental result of this study had a similar tendency to the value reported by Otsuji and Kurosawa [3].

According to the previous study Haramura and Katto [7], a liquid film exists between the mushroom bubble and the heated surface. It has been reported that CHF is generated when the liquid is all evaporated because the liquid is not supplied during the hovering period of the bubble to the liquid film formed on the heated surface. In the heaving condition, the buoyancy force of the bubble decreases with the reduced gravitational acceleration, and the hovering period of the bubble may increase due to the reduced buoyancy force. Therefore, it is assumed that CHF appears in a decreasing trend.

4.Conclusions

In this study, the heaving platform was designed to understand the CHF phenomenon under heaving conditions. A pool boiling experiment was performed according to the acceleration change due to the heaving condition.

1. To verify the device in a static situation, it was verified that it had a similar tendency as a result of repeated experiments. In a static situation, the CHF averages 1030 kW/m^2.

2. It was confirmed using a gyroscope sensor that the heaving platform was driven with a sinusoidal waveform with a maximum amplitude of 1 m and a minimum period of 3 sec. The maximum acceleration ratio is 1.501 with an error of 3.7 %, and the minimum acceleration ratio is 0.49 with an error of 11 %.

3. As a result of the experiment under heaving condition, CHF showed a tendency to decrease to the 1/4 square of the acceleration, and it was verified that the shape was similar to the CHF graph reported by Otsuji and Kurosawa[3].

The size of the test sections in this study is 10 x 15 mm^2 and it has a single steam column, but in order to check the interaction of several steam columns, a pool boiling test will be conducted with a 10x70 mm^2 test section under static and heaving conditions. The experiment was performed by changing the amplitude in the current period of 3 sec. In the future, by fixing the amplitude and changing the period, the experiment will be conducted according to the acceleration conditions of this study. Accurate acceleration data will be acquired by attaching a precise laser sensor, and it will be visualized through a high-speed camera and then analyzed.

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