Experimental observation of flow boiling CHF on a heater rod under heaving motion with working fluid of R134a

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1. Introduction

Recently, interest in FNPP (floating nuclear power plant) as one of the broad application spectrums of SMR (small modular reactor) has been increasing. Accordingly, several countries are leading the development and application of FNPP [1]. For example, Russia has developed its first FNPP, Akademik Lomonosov, including the marine reactor, KLT-40S, and has been operating since 2019 [2]. In South Korea, KEPCO E&C has announced its plan to develop a floating offshore nuclear power plant with a BANDI-60S reactor [3]. In addition, the USA (OFNP-300) [4] and China (ACPR50S) have proposed and are developing FNPP prototypes.

It has been reported that the thermal-hydraulic phenomena of floating systems can be different compared to onshore nuclear power plants due to the marine environment. Therefore, several experimental and numerical studies, particularly for two-phase flow under motion conditions, have been conducted [5]. However, the experimental data on CHF (critical heat flux) is insufficient, and the effect of additional body force on CHF has not been clearly identified. In the case of CHF under heaving motion conditions, a few studies [6, 7] have been conducted, and it has been found that CHF decreases with the increase of heaving acceleration. However, these tests were conducted under relatively low-pressure conditions compared to the PWR operating conditions, and the mechanism of CHF variation is not elucidated due to the insufficient range of the experimental parameters.

In this study, CHF measurement under the heaving motion was conducted with NEOUL-H test facility. The working fluid of the test is R134a, and the test section has an annulus geometry with a heater rod. In overall, the heaving motion led to the decrease of CHF, and parametric trend on heaving motion was confirmed.

2. Heaving experimental facility

2.1. Heaving platform, NEOUL-H

NEOUL-H is the platform that can simulate the sinusoidal heaving motion within the six-degree of freedom of motion. The primary design parameters for the heaving platform are the amplitude of cyclic heaving acceleration and heaving period. When the heaving motion is given by Eq. (1), the theoretical value of heaving acceleration can be calculated by Eq. (2).

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

where A, A_m, and T are displacement of the test loop, amplitude of heaving motion, and heaving period, respectively.

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

where a is heaving acceleration. The platform was designed to simulate acceleration of up to 0.6 g and a cycle period of 3 seconds.

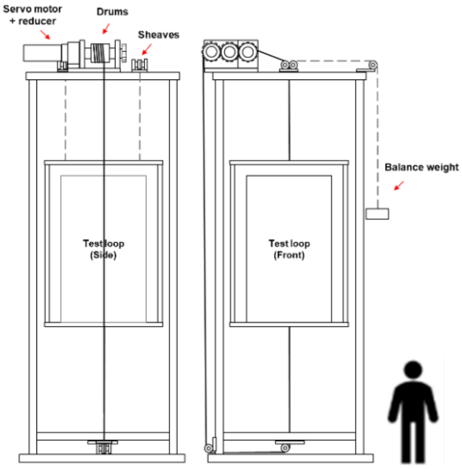

Fig. 1. Schematic of heaving platform, NEOUL-H

The main driving force of the heaving platform is provided by servo motor, and the rotational motion of the motor is converted into linear motion through drums, sheaves, and wire ropes. As depicted in Fig. 2, it was shown that the z-axis (vertical component) measurement results of the accelerations at the test section agreed well with analytic values within 5.1%.

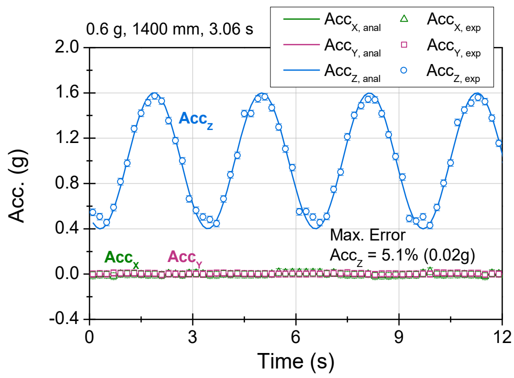

Fig. 2. Comparison results of acceleration at the test section under heaving conditions (Experimental vs. analytic values)

2.2. Test loop and CHF test conditions

The CHF test loop uses R134a as the working fluid to simulate CHF under the condition of lower pressure and heating power compared to those of water. Based on fluid-to-fluid scaling criteria, the CHF phenomenon can be preserved between two systems with different fluids. The details of similarity criteria and validation results can be found in Kim's work [8,9]. Due to the aforementioned advantages and the advantage of well-known thermal properties, R134a has been widely used in CHF experiments. The test ranges are summarized in Table I.

Table I: 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 ~ 2000	300 ~ 2500
Inlet subcooling [K]	15 ~ 43	40 ~ 120

The test section consists of a heater rod with 9.5 mm diameter and 800 mm heated length, and a 3/4-inch flow tube as shown in Fig. 3. The rod is uniformly heated, so one can expect the CHF to occur at the end of the heated length (EHL). Therefore, eight thermocouples are installed at EHL and are arranged at uniform intervals through the circumferential direction inside the clad to detect the occurrence of CHF. Under this design, one can accurately measure the circumferential temperature response at CHF, which can contribute to clarifying the mechanism of CHF. In addition, the heater rod is supported by two spacers located in the non-flow area near the flange and a supporter located in upstream location where L/D is 77 from the EHL.

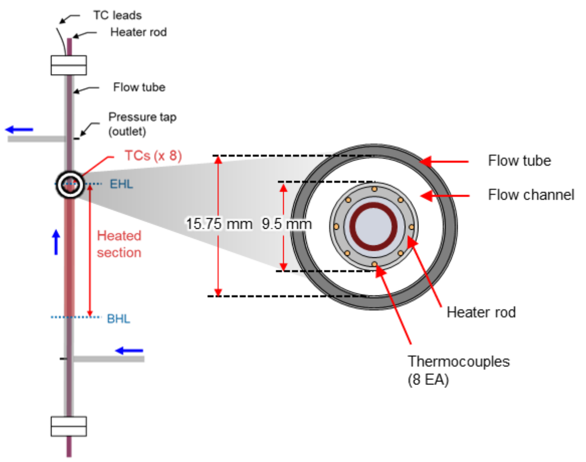

Fig. 3. Configuration of test section

The static and heaving tests were conducted for each thermal-hydraulic condition to determine the effect of the heaving motion, and the tested heaving conditions are listed in Table II. In Table II, the stroke is the distance that the test loop travels by the platform during each cycle.

Table II: Heaving conditions

Acceleration amplitude [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

3. Experimental results

This section presents the experimental results under static and heaving conditions. The CHF in static and heaving conditions is defined as the heat flux at which the wall temperature excursion occurs and the wall temperature does not stop rising until the power is cut off. The test results under the static condition could be classified into DNB and dryout based on the temperature response near the CHF and was compared to those under heaving conditions. The parametric effect of heaving motion on CHF was investigated, and two kinds of dimensionless numbers are suggested, which can represent the experimental results.

3.1. CHF under static condition

As shown in Fig. 4, DNB and dryout conditions are classified based on Katto's CHF regime map [10] and critical quality obtained from the experiments, and the experimental observation of thermocouple signals at the CHF. The classification method is the same as our previous study of the same test loop configuration [8,9]. In addition, the measured CHF value and wall temperature response near CHF showed consistent results with the previous studies [8,9].

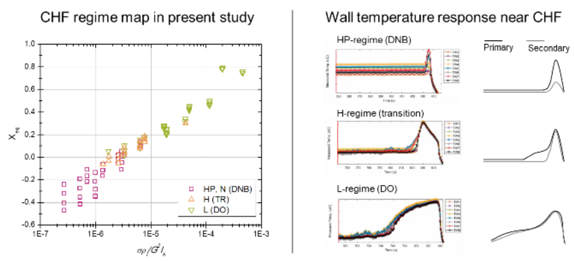

Fig. 4. CHF regime and wall temperature responses

3.2. CHF under heaving conditions

The heaving experiment was performed under the same thermal-hydraulic conditions as the static CHF test conditions. During the CHF test under heaving motion, the flow fluctuation rate was maintained at less than 2% by controlling the inlet throttling valve. This amount of flow fluctuation was expected to have little effect on CHF under heaving motion in the present experiment, and it is experimentally confirmed with supplementary tests with inlet throttling valve opened.

The temperature response under the heaving condition at the heat flux near CHF has different characteristics compared to the static condition. In heaving conditions, cyclic heaving acceleration affects the heat transfer or bubble behavior, which can result in the temporary generation of dry patches and rewetting, and this appeared in the form of periodic temperature fluctuation before CHF. This phenomenon was reported in the previous studies on rolling CHF experiments [8, 9, 11]. As shown in Fig. 5, the temperature fluctuation near the CHF condition was observed in most of the CHF cases except for high critical power with high flow rate conditions in the DNB region. In the case where the temperature fluctuation was observed, the rapid temperature increase appeared when the loop reached the top dead center of the heaving motion, which denotes the minimum net gravity condition. However, as the net gravity increased, it tended to be quenched as shown in Fig. 5. This situation was repeated continuously until it failed to be quenched due to increased power. The occurrence of temperature rise near the top dead center (at minimum net gravity) is consistent with previous studies [6, 7]. In the present study, the CHF under the heaving condition is defined as the heat flux where the temperature excursion occurs and wall temperature does not decrease without the power cut-off.

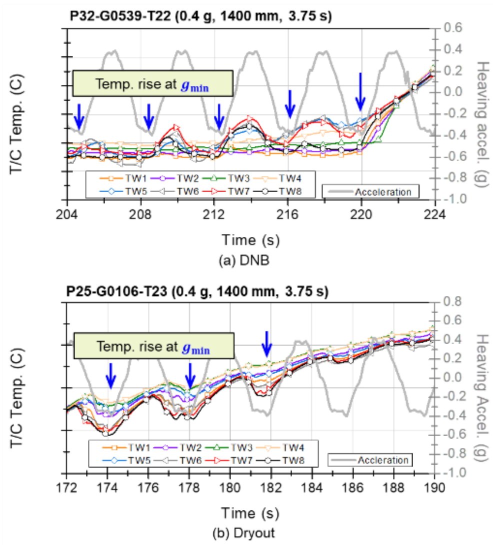

Fig. 5. Wall temperature response near CHF under heaving condition for (a) DNB and (b) dryout

The heaving motion effect on CHF was expressed as the ratio compared to the static case, defined as $CHFR_{HV/ST} = CHF_{HV}/CHF_{ST}$. In overall, the heaving motion led to the decrease of CHF as shown in Fig. 6. The error bar in Fig. 6 indicates the effects of the period of heaving motion and the inlet subcooling. The effect of heaving motion on CHF increased by increasing the heaving acceleration from 0.2g to 0.6g. The change in CHF under heaving motion was due to temporary decrease of the net gravity resulting in decreased buoyancy force on bubbles during the cyclic heaving motion. This effect increased by increasing the heaving acceleration. On the other hand, as the flow rate increased, the buoyancy effect was relatively weakened, then $CHFR_{HV/ST}$ converges to the unity.

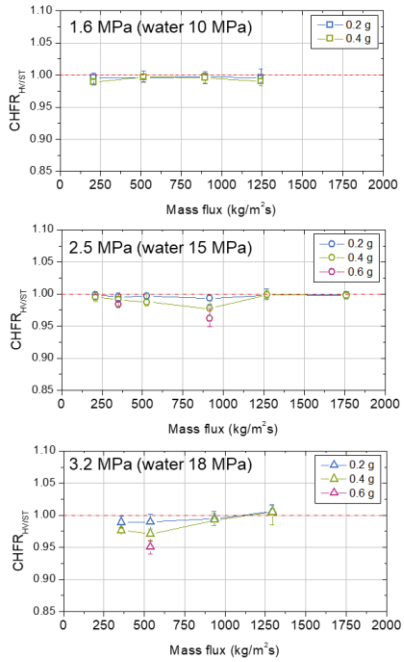

Fig. 6. Parametric effect of heaving motion on CHF

For the dimensionless number related to CHF under the heaving condition, two types of Froude numbers were proposed for DNB and dryout conditions, respectively. Because the heaving motion effect can be represented by the competition of buoyancy and flow rate, the heaving effect on CHF can be expressed by the modified Froude number, which is the ratio of the flow inertial force to the buoyancy force. The specific value of a non-dimensional number, $\sigma\rho_l/G^2 l_h = 5 \cdot 10^{-6}$.

The definition of the Froude numbers are as follows:

$$Fr_{DNB} = \frac{G(1-x_{eq})}{\rho_l\sqrt{\Delta g D(\Delta\rho/\rho_l)}} = \frac{j_l}{\sqrt{\Delta g D}}\left(\sqrt{\frac{\rho_l}{\Delta\rho}}\right) \tag{3}$$

$$Fr_{DO} = \frac{G x_{eq}}{\rho_v\sqrt{\Delta g D(\Delta\rho/\rho_v)}} = \frac{j_g}{\sqrt{\Delta g D}}\left(\sqrt{\frac{\rho_v}{\Delta\rho}}\right) \tag{4}$$

where Δg is the amplitude of cyclic heaving acceleration, j_l and j_g are the liquid and gas volumetric flux, respectively. These dimensionless numbers, Fr_{DNB} and Fr_{DO} are the modified form compared to previous studies on inclined condition [8,9] to reflect the effect of buoyancy force acting on the bubble or liquid film in the direction of parallel to the heated wall. These two numbers can represent the experimental results in DNB and dryout regime as shown in Fig. 7.

At first, in the DNB region, the buoyancy dominant region was characterized by small values of Fr_{DNB} with high amplitude of the heaving acceleration or low flow rate conditions. On the other hand, the flow dominant region was characterized by a large value of Fr_{DNB} with small heaving acceleration or high flow rate conditions. As it approached the flow dominant region, the heaving effect decreased, and $CHFR_{HV/ST}$ converges to unity. As the heaving effect gradually increased, it moves from the flow dominant region to the buoyancy dominant region. Then, $CHFR_{HV/ST}$ gradually decreased.

Secondly, in the dryout region, the increase in Fr_{DO}, which is represented by the large value of j_g, leads to the flow dominant region that CHF mechanism is governed by the flow inertia of gas phase. Then, $CHFR_{HV/ST}$ converges to the unity. As Fr_{DO} decreases with small j_g and large heaving acceleration, $CHFR_{HV/ST}$ tended to decrease slightly, but the heaving effect on CHF was shown to be limited compared to DNB region. This is because the variance of acceleration parallel to the liquid film and vapor flow is presumed to have a little effect on the entrainment and decomposition rate in dryout CHF mechanism.

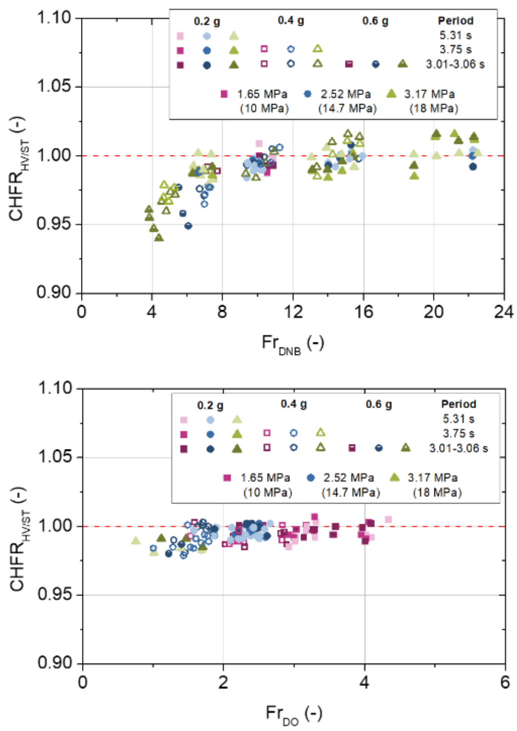

Fig. 7. Modified Froude numbers vs. $CHFR_{HV/ST}$ for DNB and dryout

4. Conclusions

In this study, CHF measurement was conducted under the heaving conditions using the NEOUL-H test facility. Heaving test conditions covered the acceleration of up to 0.6 g and 3 seconds. As a result, the acceleration of heaving motion was well simulated by sinusoidal shape. The parametric effect of heaving motion on CHF was investigated, and two kinds of dimensionless number are suggested, which can represent the experimental results.

Currently, the experiments under various thermal-hydraulic and heaving conditions are being conducted. In addition, the analyses of the experimental results are undergoing including analyses for CHF degradation mechanism and model developments. In addition, while the previous studies have been mainly focused on the acceleration amplitude with respect to CHF under heaving motion, the effect of the motion period on the CHF mechanism under heaving motion will also be investigated.

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