Commissioning test of NEOUL-H facility designed for flow boiling CHF measurement under heaving motion

Jin-Seong Yoo, Chang Won Lee, Heepyo Hong, Goon-Cherl Park, Hyoung Kyu Cho*
Department of Nuclear Engineering, Seoul National Univ., 1 Gwanak-ro, Gwanak-gu, Seoul 08826
**Corresponding author: chohk@snu.ac.kr*

1. Introduction

In recent years, interest in the FNPP (floating nuclear power plant) has been increasing, and some countries are leading the development and application of FNPP [1]. Russia has been operating FNPP, Akademik Lomonosov including its marine reactor, KLT-40S. In South Korea, KEPCO E&C has announced its plan to develop a floating offshore nuclear power plant equipped with the BANDI-60s reactor, a small modular reactor design that has been developed since 2016. In addition, several countries such as the USA (OFNP-300), China (ACPR50S) have proposed or are developing FNPP prototypes [2].

Compared with land-based nuclear reactors, the floating system undergoes complex motion conditions, such as rolling, heaving and pitching. Owing to the periodic change of the gravitational head of the system and inertial forces caused by the dynamic motions, thermal-hydraulic phenomena can be changed compared to those of the stationary conditions. Therefore, there have been increasing experimental and numerical studies [3] particularly for two-phase flow under motion conditions. However, the experimental database for the CHF (critical heat flux) are not sufficient and the effect of motion has not been clearly identified. For the CHF under heaving motion, there have been a few experimental studies [4, 5], and it was found that CHF could be degraded with increase of heaving acceleration. However, these tests were conducted under relatively low pressure conditions and the mechanism of CHF variation is not elucidated due to the insufficient range of the experimental parameters.

In this study, the NEOUL-H test facility was constructed, which incorporates the heaving platform and the critical heat flux test loop. The working fluid of the test is R134a. The test section has an annulus geometry and a heater rod is installed at the center of the test section. The heater has multiple embedded thermocouples in circumferential direction to understand the CHF phenomenon on the heater rod under heaving condition. The commissioning test results of CHF under heaving motion were described in the viewpoint of wall temperature response of a heater rod.

2. Experimental design

2.1. Heaving platform of NEOUL-H

The heaving platform can simulate the heaving motion, a translational motion for the vertical axis among the six-degree of freedom of motion. Since the actual wave can be expressed by superposition of sinusoidal waves, the heaving motion is generally assumed to be the periodic sinusoidal motion. The major design parameters for heaving platform are maximum 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. In the case of heaving acceleration, it is seen that amidships the acceleration is lowest and that the maximum value is about 0.4 g. However, depending on the sea states, a maximum heaving acceleration can be higher than 0.4 g [4]. For the heaving period, it is known that it ranges from 3.5 to 8 seconds depending on the sea states [6]. It is also reported that most cyclic periods of heaving motion of ships in the Pacific fall in the range of 3 to 12 seconds [4]. Based on these data, the platform was designed to simulate acceleration of up to 0.6 g and cycle period of 3 seconds.

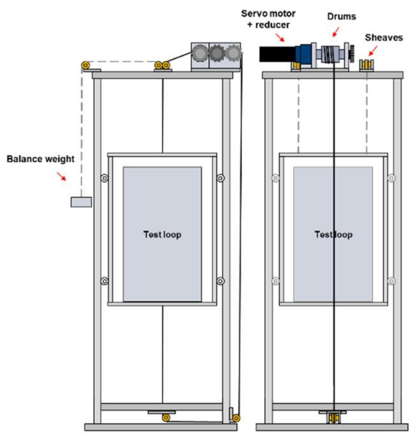

Fig. 1. Schematic of heaving platform, NEOUL-H

The main driving force of heaving platform is supplied by servo motor, and the rotational motion of servo motor is converted into linear motion through drums, sheaves, and wire ropes. The balance weight design is adopted to offset the dynamic weight of the test loop, and double drums are used to supply sufficient driving force during upstroke and downstroke, respectively. Through the precise control of servo motor and usage of reducer, the sinusoidal motion of the specific amplitude of acceleration and period is simulated. As depicted in Fig. 2, it was shown that the z-axis (vertical component) measurement result of accelerations at the test section was agreed with analytic values within 4.6%. In addition, the vertical alignment of test loop during the heaving motion is confirmed through the x-axis and y-axis measurement results.

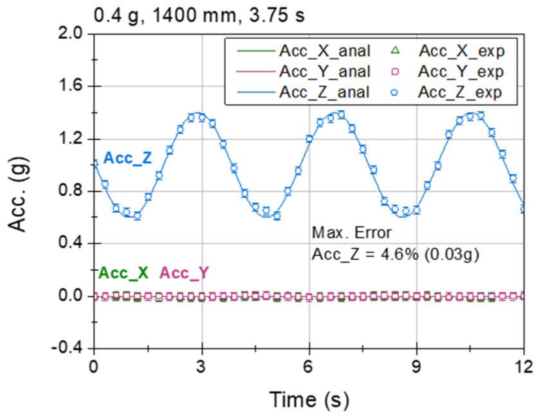

Fig. 2. Comparison result of acceleration at the test section under heaving condition (Experimental vs. analytic values)

2.2. CHF test loop of NEOUL-H

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 [6].

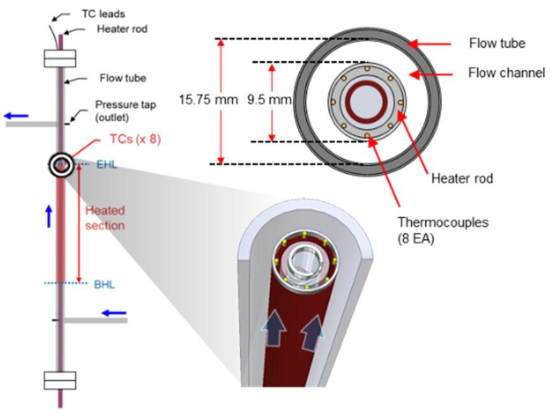

Fig. 3. Configuration of test section

As shown in Fig. 3, the test section consists of heater rod with 9.5 mm diameter and 800 mm heated length, and a 3/4-inch flow tube. The rod is uniformly heated so that 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 spacers located at the bottom and end flange, and by supporters located at the upstream location where L/D is 77 from EHL. The test ranges are summarized in Table I.

Table I: CHF test conditions

	Test conditions
Outlet pressure	2.25 ~ 3.17 MPa
Mass flux	100 ~ 1300 kg/m^2s
Inlet subcooling	22 ~ 43 K

3. Experimental design

In this section, the commissioning experimental results are summarized. The occurrence of CHF is defined as uncontrollable temperature excursion due to the abrupt deterioration of wall heat transfer. The test results under 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.

3.1. Static conditions

As shown in Fig. 4, DNB and dryout conditions are classified through the temperature response of the thermocouples under the heater rod clad. As reported in many previous studies, DNB was occurred at the condition of high pressure, high mass flux, and low inlet quality. Under these conditions, it is presumed that certain heat input causes loss of liquid access to the heated wall as small bubbles are concentrated on the heater surface and form a vapor blanket. In general, DNB occurs at much higher heat fluxes than dryout, which promotes rapid temperature rise. As shown in Fig. 4-(a), in the case of DNB, the rapid temperature rise without precursor was generally observed, but there was minor precursor right before CHF in the case of relatively low mass flux and high inlet quality conditions.

On the other hand, dryout was occurred at the condition of low pressure, low mass flux, and high inlet quality. Under these conditions, it is expected that complete evaporation of the liquid film on the heated rod causes the CHF. Compared to the DNB, the temperature continuously oscillated before the CHF as shown in Fig. 4–(b). At the CHF point, the temperature rise was slow and gradual. In addition, since the temperature rise is observed almost simultaneously in each thermocouple, the dryout position in the circumferential direction could not be specified. As can be seen from the Fig 4, there was a deviation between the temperature signals due to the difference in gap size between each thermocouple and the heater clad. These deviations can be minimized through the proper correction procedures. In this paper, however, the raw data were directly used without the procedure as the CHF can be detected with the temperature gradient and thus, it is irrespective of the temperature deviation

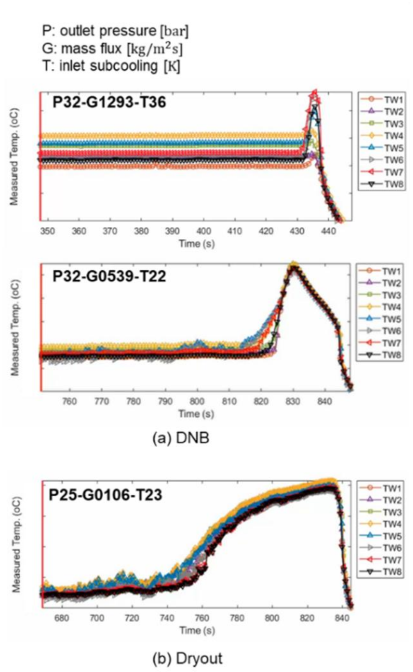

Fig. 4. Wall temperature response of heater rod for (a) DNB and (b) dryout under static condition

3.2. Heaving conditions

During the CHF test under heaving motion, the fluctuation of the flow rate was kept 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 this experiment. In the case that heaving motion is applied for the same condition described in section 3.1, the temperature response at CHF appeared as shown in Fig. 5. The heaving condition was 1400 mm and 3.75 seconds for the heaving amplitude and period, respectively. The maximum heaving acceleration is 0.4 g for the corresponding condition. Based on the temperature response before CHF, The DNB could be divided into Type-I and Type-II. Type-I corresponds with high pressure, high mass flux condition among DNB results. Under this condition, once the temperature sharply increased, quenching could not occur and the increase of temperature continued which leaded to burnout. Otherwise, relatively low mass flux conditions among DNB are classified as Type-II. In Type-II, as the loop reached the top dead center of heaving motion, which denotes the minimum net gravity condition, the temperature rapidly increased first. However, after the heaving acceleration increased, it tended to be quenched as shown in Fig. 6-(a). 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 [4, 5].

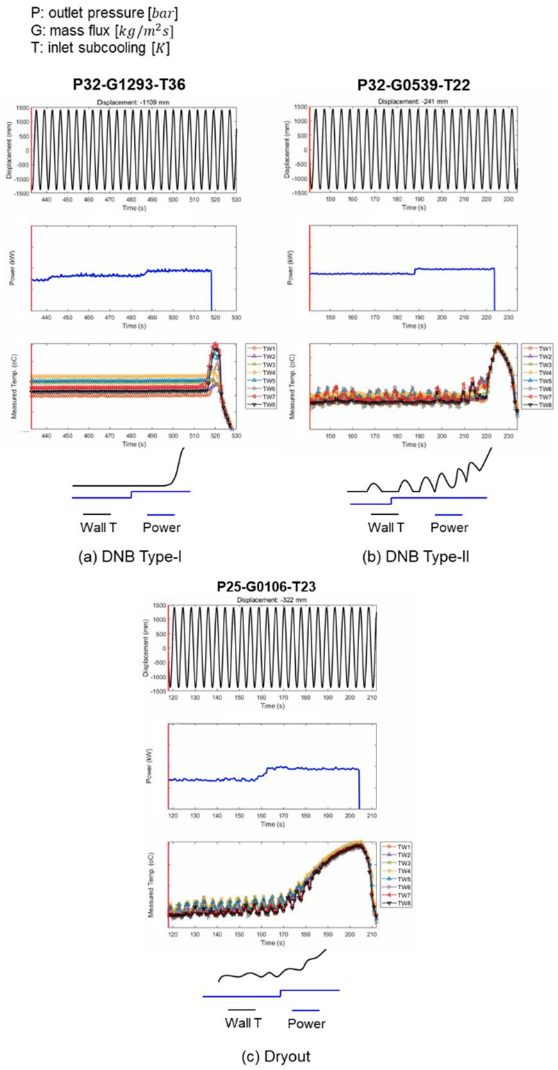

Fig. 5. Wall temperature response of heater rod for (a) DNB type-I, (b) DNB type-II and (c) dryout under heaving condition

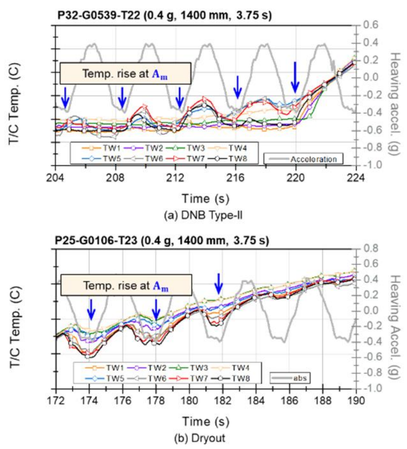

Fig. 6. Wall temperature response according to heaving acceleration change for (a) DNB type-II and (b) dryout

For dryout, in most cases, temperature rise and quenching were repeated. The rise and fall of temperature appeared in a wide area of heated surface compared to DNB. As the heat flux increased further by preventing the surface to be quenched, the temperature of the entire area tended to rise slowly with some periodic oscillation. As shown in Fig. 6-(b), the phase relationship between heaving motion and temperature rise and fall appeared the same as in the DNB Type-II.

4. Conclusions

In this study, a heaving platform was constructed and an R134a CHF test loop was installed on the platform in order to find out the mechanism of CHF phenomenon under heaving conditions. To understand the CHF phenomena on the heater rod, a heater rod with eight circumferentially embedded thermocouples was used in the experimental loop. The platform can simulate heaving up to 0.6 g and 3 seconds. As a result of the commissioning, the acceleration of heaving motion was well simulated by sinusoidal shape. The temperature responses of the heater rod under static and heaving conditions for DNB and dryout were compared.

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 enhancement or degradation 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.

REFERENCES

[1] K.H. Lee et al., Recent advances in ocean nuclear power plants, Energies, vol. 8, pp. 11470-11492, 2015.
[2] I.H. Kim et al., Development of BANDI-60S for a floating nuclear power plant, Fuel, Vol. 290, 325, 2019.
[3] Z. Tian et al., Flow boiling heat transfer under marine motions: A comprehensive review, Annals of Nuclear Energy, Vol. 143, 107455, 2020.
[4] N. Isshiki, Effects of heaving and listing upon thermo-hydraulic performance and critical heat flux of water-cooled marine reactors. Nuclear engineering and Design, Vol. 4, No. 2, pp. 138-162, 1966.
[5] T. Otsuji, and A. Kurosawa, Critical heat flux of forced convection boiling in an oscillating acceleration field-I. General trends. Nuclear Engineering and Design, Vol. 71, No. 1, pp. 15-26, 1982.
[6] G.W. Kim, Experimental investigation of critical heat flux on a single heater rod under inclined and rolling conditions, Seoul national university, 2021.