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Experimental observation of flow boiling CHF on heater rod with axially cosine shape power distribution under rolling condition

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1. Introduction

Floating Nuclear Power Plants (FNPPs) can be designed to equip Small Modular Reactors (SMRs) on marine environments, offering various benefits such as seawater desalination and providing electricity to areas with limited access to conventional power grids [1]. In this regard, Russia has achieved success in operating the FNPP, Akademik Lomonosov, which is designed to have two KLT-40S reactors, since 2019 [2]. Numerous other countries have actively pursued FNPP development including the project for OFNP-300 and ThorCon of the United States, Prodigy TNPP of the United States and Canada, CMSR of Denmark, and BANDI-60 of South Korea[3-8].

In motion conditions, thermal-hydraulic phenomena such as boiling and Critical Heat Flux (CHF) may differ from those on land, as confirmed through various experimental and numerical studies [9]. Recent studies have been conducted for CHF experiments using uniformly heated bare rods and helical rods under rolling conditions, but the effects of power profile on CHF in rolling motion have not yet been analyzed [10-13]. The fuel rods in a reactor have an axially non-uniform power profile, potentially leading to CHF occurring near the center or top of the fuel rod. Consequently, several experimental and theoretical studies have been conducted to predict the occurrence location of CHF [14]. However, available experimental data for CHF with non-uniform power profiles under motion conditions remain insufficient.

In this study, a CHF experiment was conducted using a heater rod with axially cosine shape power distribution under rolling conditions, and the locations where CHF occurred were analyzed. The motion platform NEOUL-R was utilized to simulate sinusoidal rolling conditions, and an annulus test section was employed. Additionally, to simulate the high-pressure conditions of water, the working fluid R134a was used. Overall, under the rolling condition, the CHF was increased on the heater rod with axially cosine shape power distribution, and it was also confirmed that the positions where CHF occurred were also changed.

2. Experimental facility

2.1. Rolling platform (NEOUL-R)

NEOUL-R is a platform designed to simulate rolling motion among six-degree of freedom of motion, which can perform the CHF experiments under vertical, static inclined, and sinusoidal rolling conditions [10]. In this context, the design parameters—the maximum inclination angle and the minimum rolling period—were determined to be 45 degrees and 6 seconds, respectively, based on data from the North Atlantic Ocean and IMO's 'Code of Safety for Nuclear Merchant Ships' [15, 16]. As shown in Fig. 1, to simulate rolling motion, a servo motor fixed to the floor was used, and the gear was designed as a scissors gear to prevent backlash, enabling precise adjustment of the angle. Also, to minimize the load on the gear, a balance weight was installed on top of the platform.

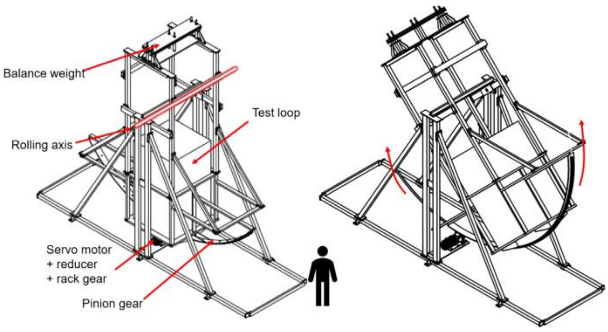

Fig. 1. Schematic of rolling platform, NEOUL-R [10]

2.2. CHF test loop and test section

The CHF test loop is designed to use R134a as the working fluid to simulate CHF under lower pressure, using less heater power compared to water. Based on fluid-to-fluid scaling criteria, experimental conditions were set as shown in Table. 1, and the details and validation of the similarity criteria were provided by Kim [10]. The P&ID of the CHF test loop was shown in Fig. 2, and the entire high-pressure primary loop is positioned on the motion platform (NEOUL-R). However, due to the motion induced by platform, phenomena such as flow oscillation may occur. Therefore, the purpose of this study was to investigate the effect of external forces on CHF resulting from inclination and rolling motion. To mitigate this, the study employed the use of a throttling valve (MCV-2) to adjust flow resistance.

Table I: CHF test conditions

	Test conditions (R134a)	Water equivalent conditions
Outlet pressure	1.6 ~ 2.5 MPa	10 ~ 15 MPa
Mass flux	100 ~ 1200 kg/m^2s	300 ~ 1800 kg/m^2s
Inlet subcooling	8 ~ 43 K	21 ~ 117 K

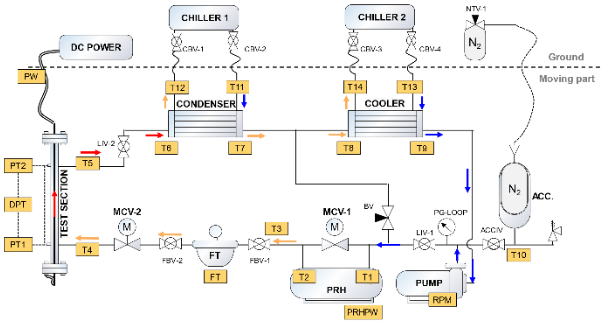

Fig. 2. P&ID of the CHF test loop

As depicted in Fig. 3, the test section consisted of an electrical heater rod with a diameter of 9.5 mm and a heated length of 800 mm, along with a 3/4-inch flow tube. Therefore, 10 thermocouples were installed on the heater rod to measure wall temperature at varying axial locations from A to E. As shown in Fig. 4, The heater rod was designed to provide cosine heat flux profile following the equation

$$q"(\mathrm{x})/\mathrm{q}"_{ave} = a + b * cos(2c(\frac{x}{l_{heated}} - 0.5)) \qquad (1)$$

where $a = 1$, $b = 0.5$, $c = \pi$, $q"_{ave}$ is the average heat flux, and l_{heated} is heated length. Therefore, the position of the thermocouples was arranged at axially different locations to detect CHF at various positions, with the greatest number of thermocouples located at position D, where CHF was expected to occur frequently. Additionally, since thermocouples are located at multiple circumferential positions, it is possible to verify the effect of inclined or rolling conditions on the occurrence of CHF at various locations.

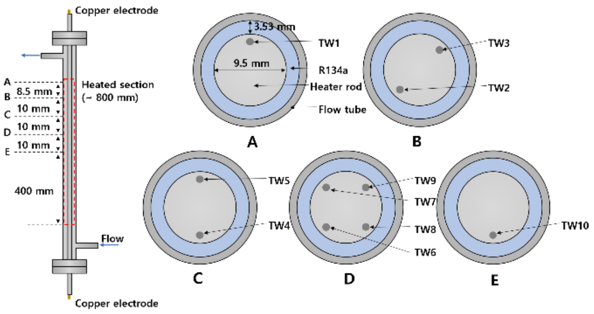

Fig. 3. Schematic diagram of the cross-sectional view of the test section

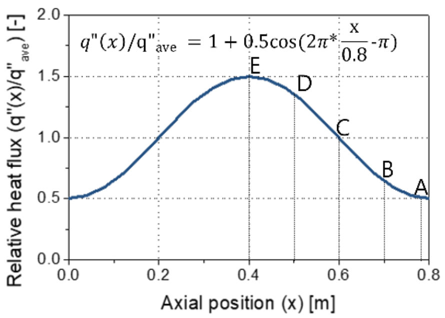

Fig. 4. Axial power profile for cosine rod heater

3. Experimental results

The experiments were conducted under both vertical and rolling conditions. Throughout the experiment, observations were made not only regarding the critical power but also regarding the location where CHF occurred.

3.1. Vertical stationary conditions

The CHF experiment under stationary condition was conducted for both dryout and DNB cases. In dryout CHF phenomena was observed under low mass flux condition. As shown in Fig. 5, with a small increase of the power, the huge increase of wall temperature was observed. In Fig. 5 – Fig. 8, to enhance visibility, only the maximum value of the wall temperature measured at each elevation (A to E) was plotted, without displaying the temperature of all thermocouples. It was confirmed that in the dryout case, initially, with an increase in power (①), dryout occurred starting from the top (elevation A), as indicated in ②. Additionally, in the next power step, as indicated in ③, the dryout area expanded, and it was observed that the temperature increased up to elevation B (④).

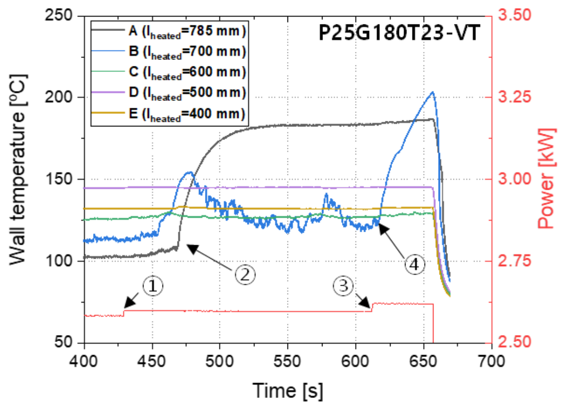

Fig. 5. Wall temperature response of heater rod for dryout case under stationary vertical condition (P = 2.5 MPa, G = 180 kg/m^{2}s, T = 23 K)

On the contrary, DNB case are primarily observed under high mass flux conditions, and the location of CHF occurrence was closer to the center of the heated length compared to the dryout case. As shown in Fig. 6, with the increasing power (①), the sharp increase in wall temperature at the elevation D (right after the center of heated length) was confirmed as indicated in ②.

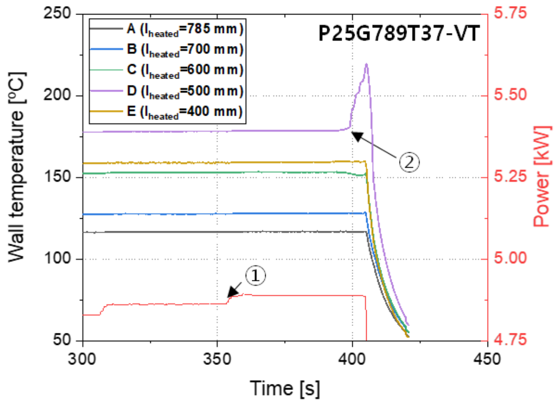

Fig. 6. Wall temperature response of heater rod for DNB case under stationary vertical condition (P = 2.5 MPa, G = 789 kg/m^{2}s, T = 37 K)

3.2. Rolling conditions

In the case of rolling conditions, different trends were observed compared to vertical stationary conditions, even under the same pressure, inlet subcooling, and mass flux conditions. In this case, during the rolling experiment, oscillations such as flow rate and pressure were limited to within 2% to mitigate their effects, enabling the examination of only the effects induced by external forces. As shown in Fig. 7, in the case of dryout case with rolling, although the inlet subcooling, pressure, and mass flux were the same as those in the vertical stationary case, a different temperature response was observed. In this scenario, with increasing power (①), the temperature rise was observed at elevation B instead of elevation A (②), similar to the DNB case, but with a relatively slower temperature increase.

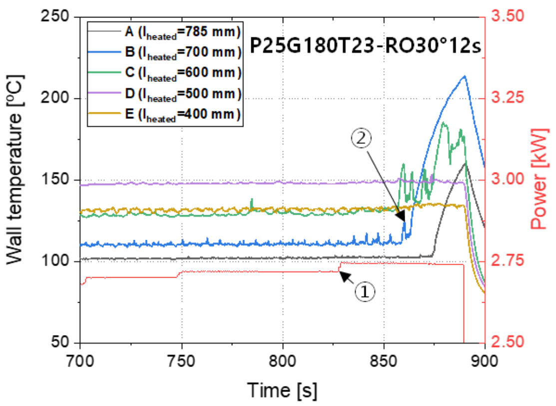

Fig. 7. Wall temperature response of heater rod for dryout case under rolling condition (P = 2.5 MPa, G = 180 kg/m^{2}s, T = 23 K)

On the other hand, for DNB case, the effect of external forces due to rolling was barely observed, mainly due to the relatively higher mass flux compared to the dryout case. Consequently, a temperature response similar to that of the vertical stationary condition was observed, as shown in Fig. 8.

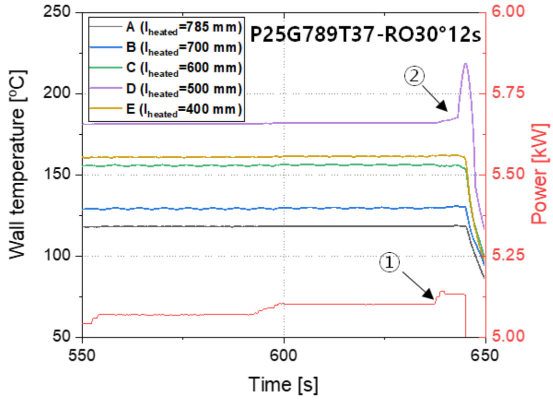

Fig. 8. Wall temperature response of heater rod for DNB case under rolling condition (P = 2.5 MPa, G = 789 kg/m^{2}s, T = 37 K)

Rolling conditions had an impact not only on the temperature response but also on the critical power and the location of CHF occurrence. As depicted in Fig. 9, the critical power was generally higher under rolling conditions compared to vertical stationary conditions, especially in the low mass flux region. Error bars were also plotted in Fig. 9 and 10 for different inlet subcooling conditions at the same pressure and mass flux. However, in some cases under high pressure, lower critical power with rolling conditions was observed. Regarding the location of CHF occurrence, results similar to those of the vertical stationary condition were observed in most cases, as shown in Fig. 10. However, when the critical power was lower compared to the vertical stationary condition, CHF occurrence tended to be closer to the center, where the heat flux is higher. Hence, it can be concluded that the variation in CHF occurrence location due to rolling conditions significantly affects the critical power.

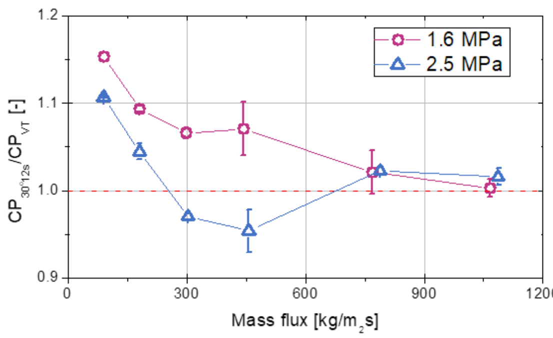

Fig. 9. Comparison of CHF between rolling at 30° with a period of 12 seconds and vertical stationary conditions

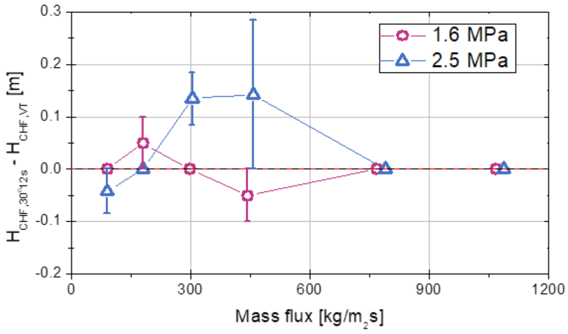

Fig. 10. Comparison of the elevation of CHF location between rolling at 30˚ with a period of 12 seconds and vertical stationary conditions

4. Conclusion

The CHF experiment under vertical stationary and rolling conditions was conducted with annulus test section using heater rod with axially cosine shape power distribution. To simulate CHF in high-pressure water, R134a was employed as the working fluid, and the temperature response at multiple positions was monitored using 10 thermocouples located inside the heater rod. The temperature trends during CHF occurrence in dryout and DNB cases under both vertical stationary and rolling conditions were analyzed. Additionally, it was confirmed that the changes in the location of CHF occurrence due to rolling have a significant role in predicting critical power.

Currently, analysis using thermocouples located on the left and right sides has not been conducted, which is necessary for observing changes in bubble behavior on the upper and lower surfaces under rolling and inclination conditions. Therefore, conducting such an analysis will be part of future work, and it is anticipated that through this, a CHF model for a non-uniformly heated rod can be developed.

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