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Commissioning test of NEOUL-R facility designed for critical heat flux measurement under rolling motion

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1. Introduction

Recently, development of remote territories has been increasing due to the growing production of coal, gas, gold, etc., and it requires reliable energy sources [1]. However, the cost of electricity transmission to these territories for long-distance can be greater than generation cost under harsh conditions. Therefore, demands for small-sized and transportable nuclear power plants are increasing to supply electricity to smaller grids and hard-to-reach areas. According to these features, the marine application of nuclear power plant has been proposed. For example, FNPP (floating nuclear power plant) including its marine reactor has been developed and under operation such as Akademik Lomonosov (KLT-40S reactor) in Russia since 2019 [2]. In addition, several countries such as the USA (OFNP-300), China (ACPR50S), and the Republic of Korea (BANDI-60S) have proposed or are developing FNPP prototypes [2].

As these marine reactors are exposed to the waves in the ocean, the reactor can continuously roll and heave. Under these conditions, 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, experimental database for the CHF (critical heat flux) are not sufficient and its effect by motion is not clear especially under rolling motion. Previously, the experimental study for CHF on a tube under rolling motion [4] had been conducted using simulant fluid for flow boiling condition. It was found that CHF could be enhanced or degraded depending on DNB (departure from nucleate boiling) or dryout regime. However, the mechanism of CHF variation is not elucidated and limited to hypothetical one due to the lack of measurement data of CHF position and limitation of rolling platform. Besides, CHF study on a heater rod under rolling condition has not been conducted or published in open literature despite of the wide application of rod geometry in fuel design for commercial reactors.

In this study, the NEOUL-R test facility was constructed, which incorporates the rolling 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 detect the circumferential position of the CHF under rolling condition. The commissioning test results of CHF under rolling motion were described in the view point of wall temperature response of a heater rod.

2. Experimental design

2.1 Rolling platform of NEOUL-R

The rolling platform can simulate the rotational motion for a single axis among the six-degree of freedom of motion. Rolling is generally assumed to be periodic sinusoidal motion because actual ocean waves can be expressed by superposition of sinusoidal motions. The main design parameters are the maximum rolling angle, period, and rolling radius. In the case of rolling angle, the maximum value is 45 degrees stated in IMO, 'Code of safety for nuclear merchant ships' [5]. There is no specific requirement for rolling period. However, according to the North Atlantic Ocean data [6], it is known that it ranges from about 7.5 to 20 seconds depending on the sea states. Based on these data, the platform was designed to simulate up to 45 degrees and 6 seconds period. The radius of rolling is a design parameter that should be determined by the reactor prototype. As the data on the radius in open literature is very limited, the data of Taymyr nuclear icebreaker and Savannah nuclear merchant ship [7, 8] were referred to. According to them, it could be estimated that the reactors had heights of about 8 m. Thus, the center of gravity was assumed to be positioned lower than 4 m of height. Based on this estimation, the radius scale was determined within 4 m.

As shown in Fig. 1, the main driving force of rolling is servo motor and its rotating power is converted into rolling motion at the end of the rolling radius through the rack-pinion gear. To eliminate the backlash caused by the use of gears, the scissors gear was used and the balance weight design was adopted to offset the weight of test loop under rolling motion. Through the precise control of servo motor and usage of reducer, the sinusoidal motion is simulated. As depicted in Fig. 2, it was shown that the measurement result of accelerations at the test section was agreed with analytic values within 1.7 %.

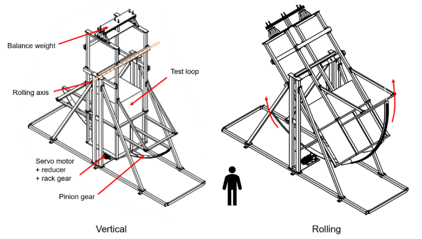


Fig. 1. Configuration of rolling platform, NEOUL-R

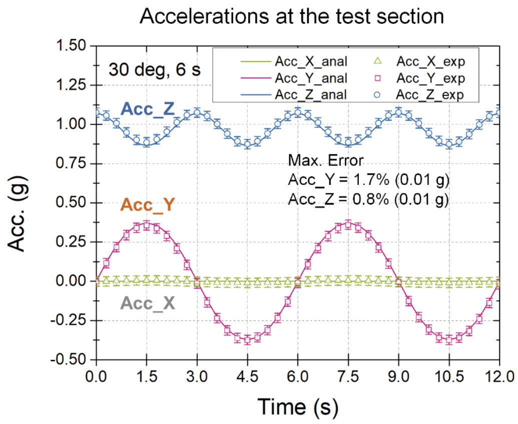


Fig. 2. Comparison result of acceleration at the test section under rolling condition (Experimental vs. analytic values)

2.2 CHF test loop of NEOUL-R

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. In the similarity criteria, the following three variables should be preserved between two systems.

$$\left(\frac{\rho_f}{\rho_g}\right)_{R134a} = \left(\frac{\rho_f}{\rho_g}\right)_{Water} \quad (1)$$

where ρ is density of fluid, subscript f and g indicate the liquid and vapor.

$$\left(\frac{G\sqrt{D}}{\sqrt{\sigma\rho_f}}\right)_{R134a} = \left(\frac{G\sqrt{D}}{\sqrt{\sigma\rho_f}}\right)_{Water} \quad (2)$$

where G, D, and σ are mass flux, hydraulic diameter, and surface tension, respectively.

$$x(z) = \frac{1}{h_{fg}}\left[\frac{q''A_{heat}}{GA_{flow}} - \left(h_f - h_{in}\right)\right] \quad (3)$$

where x, h, q'', and A are thermodynamic quality, , fluid enthalpy, heat flux, and area, respectively. Firstly, in the Eq. (1), density ratio between liquid and vapor can be preserved by pressure condition. Secondly, the mass flux scaling parameter in Eq. (2) should be preserved between two systems. This scaling factor was proposed by Katto [9] and it was adopted in this study because the previous study showed that Katto model had better prediction capability in fluid-to-fluid scaling of CHF rather than the other model of Ahmad [10]. Lastly, the inlet subcooling can be determined by preserving the thermodynamic equilibrium quality in Eq. (3) at the position of CHF.

As shown in Fig. 3, The test section consists of heater rod with 9.5 mm diameter and 800 mm heated length, and 3/4-inch flow tube. The rod is uniformly heated so that one can expect the CHF to occur at the end of heated section (EHL). Therefore, the eight thermocouples are installed at EHL and evenly spaced through circumferential direction inside the clad to detect the occurrence of CHF. Under this design, one can accurately measure the location of CHF, which could be an important result in clarifying the mechanism of CHF under rolling conditions. In addition, the heater rod is supported by spacers located at the bottom and end flange, and by supporters located at the upstream location of which L/D is about 72 from inlet at 77 from EHL. The test ranges are summarized in Table I.

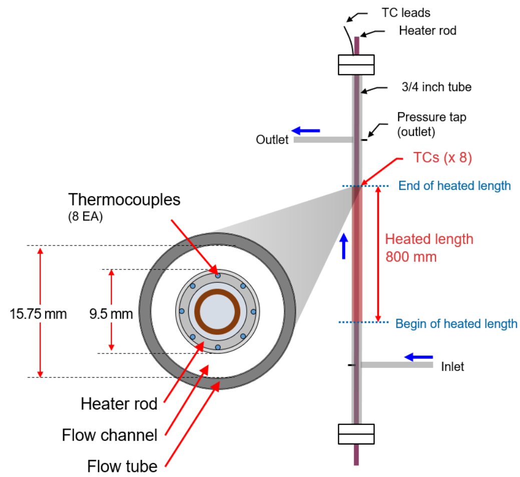


Fig. 3. Configuration of test section

Table I: CHF test conditions

	Test conditions
Pressure	1.65 ~ 3.17 MPa
Mass flux	360 ~ 1800 kg/m^{2}s
Inlet subcooling	15 ~ 43 K

3. Experimental results

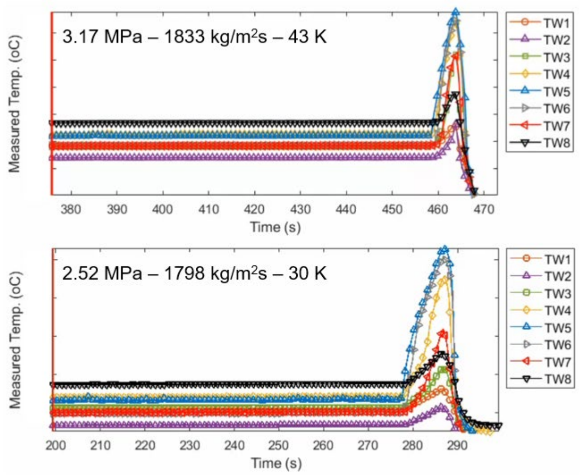
In this section, the commissioning test results are summarized. The occurrence of CHF was detected by the abrupt rise of wall temperature due to deteriorated wall heat transfer. Afterward, it was classified into DNB and dryout according to the trend of temperature response near the CHF. Lastly, the temperature responses under DNB and dryout conditions were compared for the stationary vertical and rolling conditions.

3.1 Vertical stationary conditions

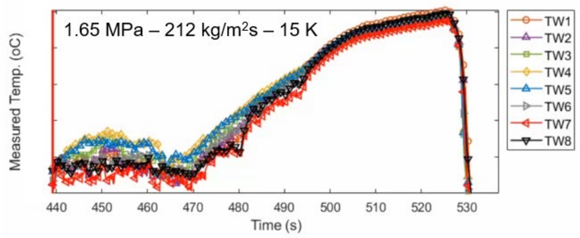
As shown in Fig. 4, DNB and dryout conditions are distinguished through the temperature reaction of the thermocouple installed beneath the clad of the heater rod. As previously reported in numerous CHF studies, DNB appeared under high pressure, high mass flux, and low-quality conditions. It is expected that small bubbles are clustered on the heater surface making vapor film. The temperature rise occurred very rapidly, and there was insignificant precursor of DNB right before CHF as shown in Fig. 4–(a). The point at which the temperature rise varied depending on the thermal-hydraulic test conditions.

On the other hand, dryout appeared under low pressure, low mass flux, and high-quality conditions. Under the conditions, it was expected that thin liquid film was dried on the heated wall. Compared to the DNB, the temperature continuously oscillated before the CHF. At the CHF point, the temperature rise was slow and gradual as shown in Fig. 4–(b). In addition, the circumferential position of the dryout cannot be specified and the temperature rose gradually almost simultaneously.

As can be seen from the Fig 4, there was a deviation between the temperature signals of thermocouples due to the variance of the gap sizes existing between each thermocouple and the heater clad. These deviations can be minimized with a proper correction procedure. 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.



(a)
DNB



(b)
Dryout

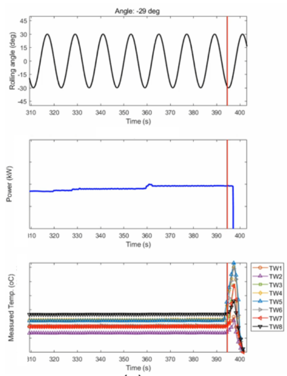
Fig. 4. Wall temperature response of heater rod for (a) DNB and (b) dryout under stationary vertical condition

3.2 Rolling conditions

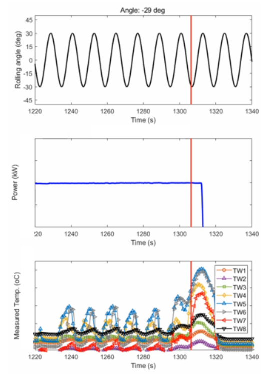
In the case that rolling motion is applied for the same condition described in Section. 3.1, the temperature response at CHF appeared as shown in Fig. 5. The rolling condition was 30 degrees and 12 seconds for the angle and periods, respectively. Based on the temperature response before CHF, the DNB 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. While in the case of Type-II, it corresponds with relatively low-pressure conditions among DNB. As the rolling angle reached the maximum value, the temperature rapidly increased first. However, after the angle decreased, it tended to be quenched. This situation was repeated continuously until it failed to be quenched due to unstable conditions or increased power. When the quenching failed, the temperature rose to be burnout. The position of CHF appeared in a specific area.

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 with 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.

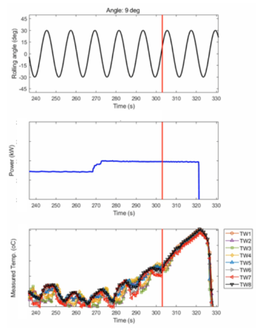
From the above results, the occurrence of CHF under rolling could be defined similarly to the vertical condition. As a result, the DNB or dryout can be defined as the point at which the heater wall is expected to be unquenchable and will continue to rise and lead to burnout.



(a)
DNB Type-I
(3.17 MPa – 1833 kg/m^{2}s – 43 K)



(b)
DNB Type-II
(2.52 MPa – 1798 kg/m^{2}s – 30 K)



(c)
Dryout
(1.65 MPa – 212 kg/m^{2}s – 15 K)

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

4. Conclusions

In this study, a rolling platform was constructed and a R134a CHF test loop was installed on the platform in order to understand the mechanism of CHF phenomenon under rolling conditions. To detect the position of CHF, a heater rod with circumferentially eight embedded thermocouples was used in the experimental loop. The platform can simulate rolling up to 45 degrees and 6 seconds. As a result of the commissioning, the angle of rolling motion was well simulated by sinusoidal shape. The temperature responses of the heater rod under vertical and rolling conditions for DNB and dryout were compared.

Currently, the experiments under various thermal-hydraulic and rolling conditions are being conducted. In addition, the analyses of the experimental results are undergoing including the validation of fluid-to-fluid scaling, analyses for CHF enhancement or degradation, positions of DNB or dryout, and model developments.

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