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Experimental investigation of CHF on helical finned heater under the static inclination and rolling conditions

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1. Introduction

Recently, there have been demands for a transportable small-sized nuclear power plant for a stable energy supply to remote territories. For example, a floating nuclear power plant (FNPP) has developed in Russia, the United States, and China [1]. And KEPCO-E&C performed the basic design of BANDI-60s, a type of FNPP, and system analysis was performed under the stationary condition [2]. However, unlike commercial nuclear systems, for nuclear power in the ocean, it is necessary to develop a model and safety analysis method that considers the additional acceleration caused by ocean motion. A few studies have been conducted to evaluate the effect of the marine environment on CHF [3, 4]. In particular, the CHF of a bare rod under the rolling condition using the NEOUL-R rolling motion platform has been studied at Seoul National University [5].

A fuel rod with a shape of helical cruciform was designed in MIT and proposed for the power uprate of an existing commercial nuclear reactor. Helical cruciform fuel rod has the advantage of superior heat transfer performance because the ratio of volume to heat transfer area is larger than that of the cylindrical rod. Furthermore it has the inherent capability of self-support for each other and good lateral mixing performance [6]. In addition, three helical petals shape fuel similar to helical cruciform fuel has been used in a marine reactor in Russia [7, 8].

In this study, a CHF experiment under vertical, static inclination, and rolling conditions using the NEOUL-R platform was performed to evaluate the applicability of a helical finned heater in marine conditions. As a result, based on the measured wall temperature behavior, the cause of CHF changes according to motion will be suggested.

2. Experimental facility

2.1. Rolling platform, NEOUL-R

NEOUL-R is a platform that can simulate rolling motion which marine reactors, including floating nuclear reactors, can be exposed. The main motion parameters are the maximum roll angle, period and roll radius. As shown in Eq. (1), a sinusoidal motion which is determined by the maximum roll angle (θ_{max}) and period (T) was simulated. The maximum roll angle of the platform is 45°, the maximum roll period is 6 seconds, and the rolling radius is about 4 m. In this study, CHF was measured under static vertical, static inclination and rolling conditions of 30°/12s, 30°/6s, 45°/12s and 45°/6s [9, 10].

$$\theta_{rolling} = \theta_{max} \sin\left(\frac{2\pi t}{T}\right) \quad (1)$$

2.2. Test section

As shown in Fig. 1, there are an inlet near the bottom and an outlet near the top of the test section. R134a, a simulant fluid, was used as coolant under conditions corresponding to operation conditions through fluid to fluid scaling [5]. The heater spirally wrapped in the counterclockwise direction by four fins was used to observe the helical fins effect on CHF, similar to MIT's helical cruciform fuel design. The fins are shifted 45° from the rolling axis in the end of heated length (EHL). In the heater rod, axially uniform heat flux was generated by a filament in the heater, so it is expected that CHF occurs at the EHL. Since the wall temperature rapidly increases when CHF occurs, eight thermocouples were inserted at circumferentially equal intervals around four fins to observe CHF. CHF was expected to occur mainly at the fin root in the helical finned heater geometry, so thermocouples were not inserted at the fin. The power was increased stepwise by about 1% until CHF occurred, and the power was lowered when it was observed that the wall temperature rapidly increased. The inlet temperature, pressure, and mass flow rate were kept almost constant even under the rolling conditions, as specific values shown in Table I.

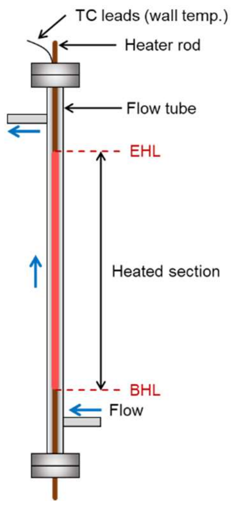

Fig. 1. Schematics of test section

Table I: CHF test conditions

Thermal hydraulic parameter	Test conditions
Pressure	1.65 ~ 3.17 MPa
Mass flux	100 ~ 1800 kg/m^{2}s
Inlet subcooling	8 ~ 43 K

3. Experimental results

In this section, the results of CHF experiments using a helical finned heater under vertical, inclination and rolling motion are summarized. Because the heat flux of helical finned heaters is different at the fin root and fin tip, further analysis is required to obtain the critical heat flux. Therefore, to observe the effect of the spiral fin, the critical power, which means the power when CHF occurs, was compared between the bare rod and the helical finned heater. In general, it has been expected that the heat transfer performance of a helical finned heater will be improved for two reasons: the presence of fins increases the heat transfer area, and the swirl flow around the heater occurs due to the helical shape. Nevertheless, there were concerns that bubbles trapped by fins would cause CHF deterioration [11]. After that, the CHF changes under the static inclination and rolling conditions of the helical finned heater were evaluated.

3.1. CHF under vertical condition

As shown in Fig. 2, the critical power of the helical finned heater is 12.7% greater on average than that of the bare rod heater in the same thermal-hydraulic conditions (mass flux, pressure, inlet subcooling). As in the previous study, the CHF regime was classified for each thermal-hydraulic condition based on Celata's method that there is a specific quality in which the regime changes. Moreover, wall temperature behaviors were used for classification [5, 12]. In the dryout regime, the gas phase is expected to occupy most of the flow area, and in the DNB regime, the liquid phase is expected to occupy most of the flow area. Therefore, as shown in Fig. 3, the superficial gas velocity in the dryout regime and the superficial liquid velocity in the DNB regime were found as significant parameters for critical power enhancement. Superficial velocities are calculated by using thermal equilibrium quality at the EHL. As described in Fig. 3(a), in the dryout regime, the greater the superficial gas velocity, the greater the critical power enhancement by the helical fin. The swirl flow by four fins strengthens droplet entrainment from the thick liquid film on the flow tube wall and fin where the temperature is relatively low, and these droplets are supplied to the fin root where dryout is expected to occur mainly. In the DNB regime, the smaller the liquid velocity and subcooling, the smaller the superficial liquid velocity. As shown in Fig. 3(b), the smaller the superficial liquid velocity, the greater the critical power enhancement by the fin. When the superficial liquid velocity is small, the bubble does not move along the liquid streamline but moves in the direction of buoyancy because the gas-liquid interface shear is small. Since these bubbles are easy to depart from the heated surface by colliding with the fin, it is expected to increase the critical power.

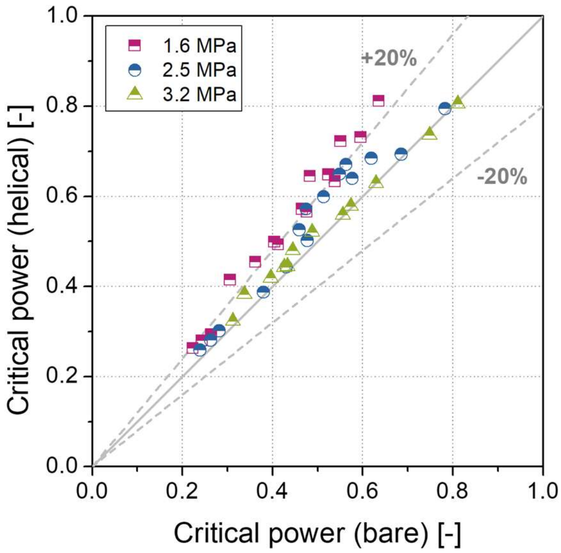

Fig. 2. Comparison of critical power between bare rod heater and helical finned heater

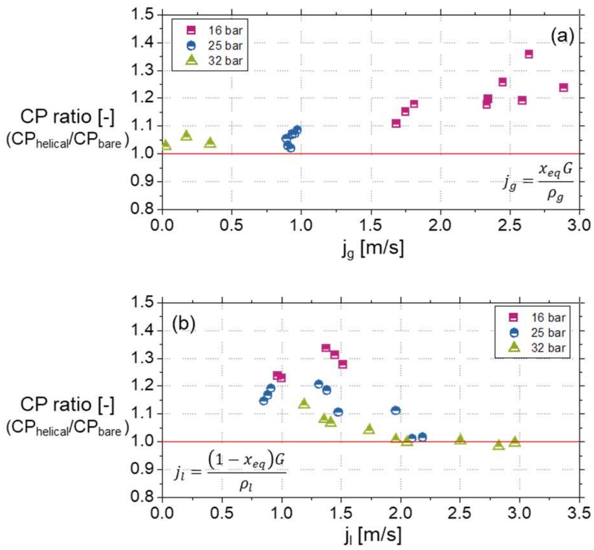

Fig. 3. The critical power ratio of bare rod heater and helical finned heater (a: dryout regime, b: DNB regime)

3.2. CHF under static inclination condition

The CHF experiments in the inclined condition were performed by changing the inclination of the test loop to ±30° and ±45° as shown in Fig. 4 under the same thermal-hydraulic conditions as the CHF experiment in the vertical condition. The change in CHF of static inclination condition compared to CHF of vertical condition was expressed as a ratio defined as

$CHFR=CHF_{IN}/CHF_{VT}$. As a result of previous experiments using bare rods, CHFR is greater than 1 in most thermal-hydraulic conditions [5]. However, in the case of helical finned heaters, there were differences in CHFR tendency for each CHF regime determined under vertical condition test results. In the dryout regime, most of the CHF increased under the inclined condition, but in the DNB regime, the CHFR mainly was about 1. Because the direction of buoyancy and flow are not parallel in the inclination condition, the competition between the buoyancy force and flow inertial force affecting CHF was expressed as the effect of inclination. Therefore, in previous studies, Fr_{DNB} and Fr_{DO} were proposed as main parameters based on the results of bare rod experiments (Eq. (2) and Eq. (3))[5, 13].

$$Fr_{DNB} = G/\rho_l\sqrt{gcos\varphi D(\Delta\rho/\rho_l)} \quad (2)$$

$$Fr_{DO} = Gx_{eq}/\rho_v\sqrt{gcos\varphi D(\Delta\rho/\rho_v)} \quad (3)$$

As shown in Fig. 5, CHFR of the helical finned heater decreased and increased according to Fr_{DO} and Fr_{DNB}, respectively, in the dryout and DNB regimes. In the dryout regime, the larger the Fr_{DO}, the higher the CHFR because the droplet entrainment in the cold wall is strengthened due to the high velocity of gas-phase and then the droplet can be deposited on the upper heated wall as illustrated in Fig. 6(a). In the DNB regime, because the Fr_{DNB} is large enough, the influence of flow inertia is small, and the CHFR is close to 1. However, unlike CHF of bare rod heater under inclination conditions, many cases with CHFR less than 1 were found. In the case of that CHFR is less than one due to early CHF occurring in the inclined condition, the wall temperatures were measured as shown in Fig 7. In both +45° and -45°, CHF is triggered around a specific fin on the lower surface at EHL. As illustrated in Fig. 6(b), the reason for CHF deterioration under the inclined condition of the helical finned heater is due to the accumulation of bubbles on the lower surface by a fin structured from the side to the lower surface. In other words, when inclined at positive and negative angles, as shown in Fig. 7, early CHF occurred in lower surface at EHL, respectively.

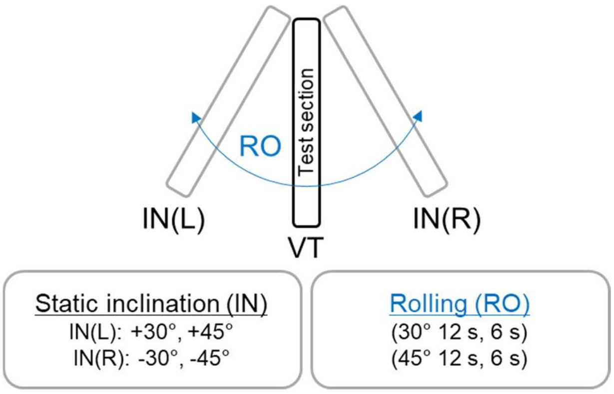

Fig. 4. Static inclined and rolling conditions in NEOUL-R

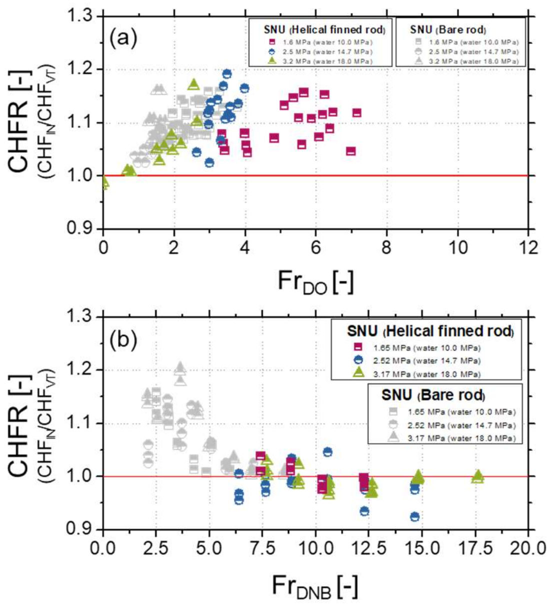

Fig. 5. Froude number Vs. CHFR
(a: dryout regime, b: DNB regime)

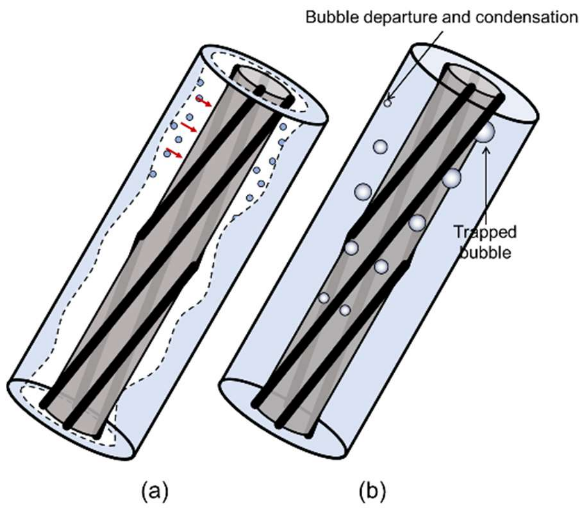

Fig. 6. Schematics of CHF enhancement and deterioration mechanism under the inclined condition
(a: dryout regime, b: DNB regime)

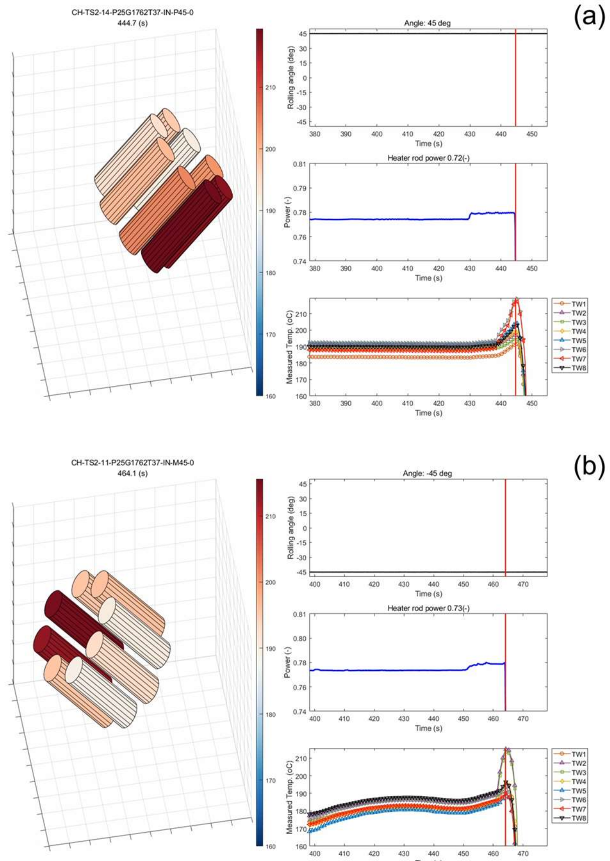

Fig. 7. Wall temperature behavior at EHL of CHF deterioration case under the inclined condition (a: +45°, b: -45°)

3.3. CHF under the rolling condition

Experiments were performed under four rolling conditions (30°/12s, 30°/6s, 45°/12s and 45°/6s) for the same thermal-hydraulic conditions as the previous static vertical and inclination condition experiments. In the dryout regime, CHF under rolling conditions occurred between CHF under vertical and inclined conditions. This is because the tangential force always acts opposite to the buoyancy force. Therefore, droplet deposition enhanced by buoyancy is slightly reduced by tangential force. As a result most of the data of the dryout regime are in the fourth quadrant in Fig. 8, which is drawn with $CHFR_{IN/VT}$ and $CHFR_{RO/IN}$ as the x and y-axis, respectively. Although the helical finned heater had similar $CHFR_{IN/VT}$ to the bare rod heater, it was observed that the effect of rolling motion was small. In the DNB regime, $CHFR_{IN/VT}$ is smaller than 1 because the fin traps the bubble under inclined conditions. When the platform reached -45° under rolling conditions or static inclination of -45°condition, the wall temperature near the upper and lower fins were described according to the step increased power in Fig. 9. Higher wall temperature, especially near the lower fin was observed in the rolling condition than in the inclination condition at the same power. Therefore, since the tangential force always acts as the opposite of the buoyancy force as shown in Fig. 10 and helps the bubble to be pulled down by the fin, CHF under the rolling conditions decreases more than CHF under the inclined condition in the DNB regime, so that $CHFR_{RO/IN}$ is less than 1 (y<1).

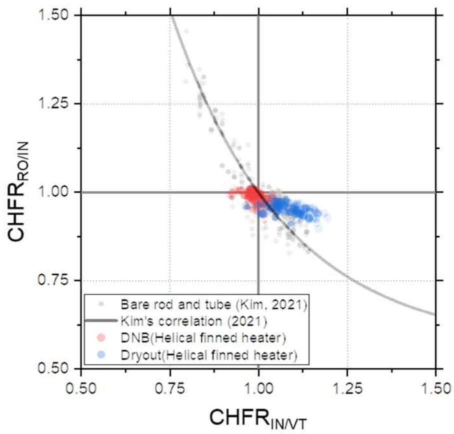

Fig. 8. CHF relations between vertical, inclined, and rolling conditions

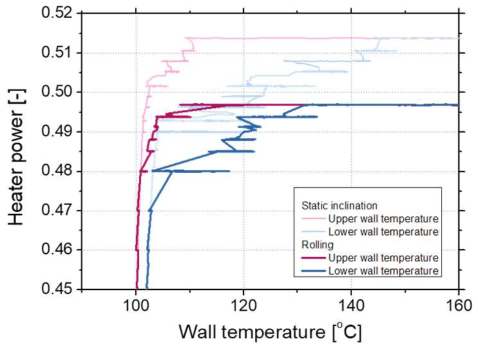

Fig. 9. Wall temperature behavior near the upper and lower fin according to the heater power under inclination condition (+45°) and rolling condition

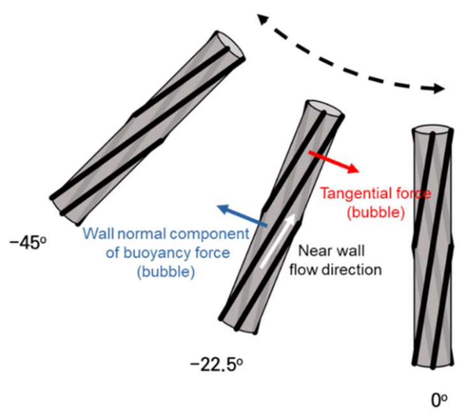

Fig. 10. Schematics of tangential force and buoyancy force acting on the bubble under the rolling condition

4. Conclusion

The effects of helical finned geometry on CHF under vertical, inclination and rolling conditions were studied. The following are the observed characteristics of the helical finned heater observed in each motion condition.

-Stationary vertical condition

Since access to the vertical CHF correlation or look-up table for the shape of the four fins spirally-wrapped rod is limited, it was investigated how critical power is improved compared to the bare rod heater. As a result, superficial gas and liquid velocity were suggested as major parameters determining the enhancement of critical power in dryout and DNB regimes, respectively.

-Static inclined condition

Under the inclined condition, the degree of CHF change was determined by the ratio of the buoyancy force and flow inertia in the previous study. However, it was observed that under the DNB regime, bubbles may accumulate on the downward surface of heater due to the structure of the helical fin, which may lead to early CHF.

- Rolling condition

As confirmed in previous studies, when CHF was increased or decreased in the inclined condition compared to the vertical condition, the buoyancy effect was ramped due to the inertia force due to rolling, especially the tangential force. Therefore, the CHF under rolling conditions was measured between the CHF under vertical and the CHF under inclined conditions. However, some DNB regime data showed that CHF deteriorated again under rolling conditions. It was found that bubble accumulation at the downward facing heated wall was increased due to the tangential force.

In this study, the behavior of the two-phase could not be directly observed at the time of the boiling crisis, but the mechanism of CHF changes of the helical finned heater by motion could be predicted based on the measured wall temperature behavior. Based on these experimental results, it is expected that a subchannel scale analysis methodology or a CHF model of a helical finned rod under motion conditions can be developed.

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