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Experimental investigation of helical fin effect on CHF under the inclined condition

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1. Introduction

Globally, research and development efforts are intensifying to utilize sustainable energy in marine environments. As part of these efforts, several nations are exploring the option of mounting nuclear power plants on non-self propelled barges to supply electricity, process heat, and desalination to remote areas [1, 2]. Such nuclear systems are termed floating nuclear power plant (FNPP). When deploying nuclear energy in ocean platforms like the FNPPs, the spatial and weight constraints often necessitate a compact reactor design [3]. The tight lattice rod bundle of helical-shaped fuel stands out as a potentially viable option. Helical-shaped fuel, owing to its fin or petal structures, offers an expanded heat transfer area. Additionally, its helical shape promotes lateral mixing, leading to the anticipation of enhanced thermal performance. However, there is a lack of accessible literature of thermal-hydraulic characteristics such as critical heat flux (CHF), pressure drop, and heat transfer coefficient. In the present study, the CHF on a helical finned heater were measured under inclined conditions, one of the ocean conditions that reactors on the ocean platform can encounter. Separate effect of swirl flow on CHF was defined based on the CHF mechanism observed under the inclined condition. After that, factors dictating the helical fin effect were identified.

2. Test facility and experimental conditions

Recently, the NEOUL-R, a rolling platform capable of simulating inclined and rolling conditions, was constructed [4]. In this study, experiments were conducted using a CHF test loop on NEOUL-R. In the test loop, a test section and a helical finned rod were equipped, as depicted in Fig. 1. The tests were conducted under inclinations of 0°, ±30°, and ±45°, as shown in Fig. 2. The rod is helically wrapped with four fins in a counterclockwise direction, following the right-hand rule. Experiments were performed under thermal-hydraulic conditions corresponding to the operating conditions of PWRs using simulant fluid (R134a). Test conditions were summarized in Table I. The thermal-hydraulic conditions were calculated based on the Katto scaling model. Details about the test facility and test conditions can be found in studies of Kim and Lee [4,5].

Table I. CHF test conditions

Thermal hydraulic parameter	Water condition	Test conditions
Pressure [MPa]	5 ~ 18	0.8 ~ 3.2
Mass flux [kg/m^2s]	300 ~ 2500	200 ~ 1800
Inlet subcooling [K]	21 ~ 117	8 ~ 43

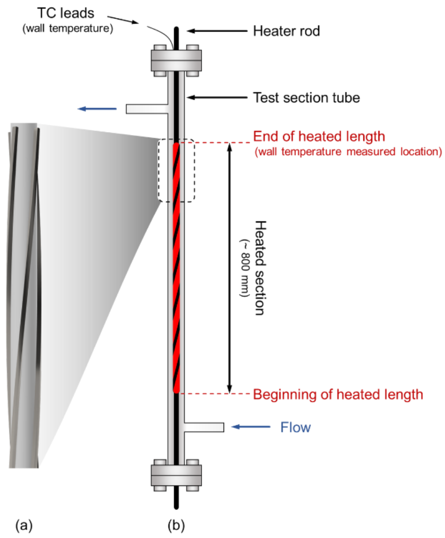

Fig. 1. Schematic diagram of the test section and helical-finned heater rod [5] (a: side view of the helical-finned heater; b: diagram of the test section)

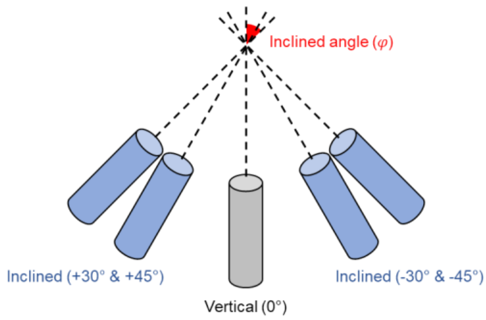

Fig. 2. Schematic diagram of static vertical and inclined conditions

3. Experimental results

In previous research, the inclination effect on bare rod CHF was expressed as the ratio of inclined CHF to vertical CHF, denoted as $CHFR_{IN/VT}^{bare}$ [6]. In their study, the trend of $CHFR_{IN/VT}^{bare}$ was elucidated based on the proposed Froude number for different CHF regimes. Under most thermal-hydraulic conditions, the normal component of gravity to flow direction led to an increase in CHF for bare rods. However, in this study, when the mass flux is high and the critical quality is low, $CHFR_{IN/VT}^{helical}$ is found to be less than 1 (Fig. 3). $CHFR_{IN/VT}^{helical}$ and the equilibrium quality at the end of heated length (denoted as x_{eq}) are defined as follows:

$$CHFR_{IN/VT}^{helical} = CHF_{IN}^{helical} / CHF_{VT}^{helical} \quad (1)$$

$$x_{eq} = \frac{h_{in} + \frac{Q}{\dot{M}} - h_g}{h_{fg}} \quad (2)$$

Where, h_{in} represents the inlet enthalpy, Q is the heating power, $\dot{M}$ stands for mass flow rate, h_g is the saturated vapor enthalpy, h_{fg} is the latent heat. The subscripts "IN" and "VT" refer to inclined and vertical conditions respectively, while the superscript "$helical$" denotes the helical finned rod.

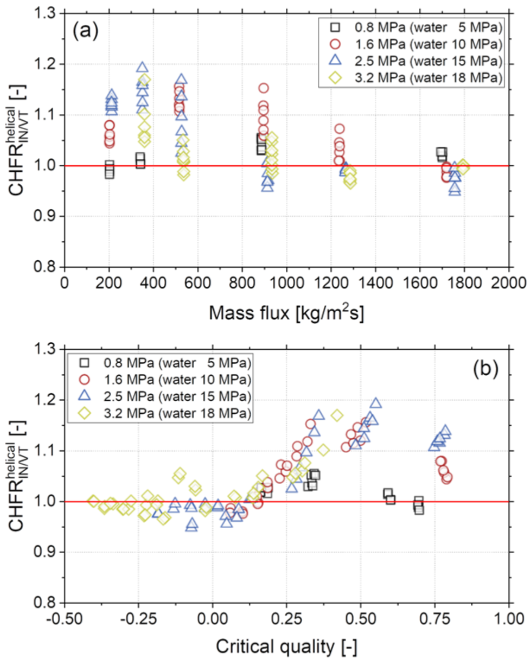

Fig. 3. Parametric trends of $\boldsymbol{CHFR_{IN/VT}^{helical}}$ (a: mass flux effect, b: critical quality effect)

According to Lee's study, the CHF on helical finned rod under inclined conditions was determined by two main mechanisms, as illustrated in Fig. 4 [5]. Both in the DNB and dryout regimes, the swirl flow was a contributing factor to the decrease in CHF under inclined conditions. Conversely, the wall normal component of gravity served as a factor leading to an increase in CHF. Shortly, the combined effects of the CHF decrease mechanism (swirl flow) and the CHF increase mechanism (gravity) determine the CHF on the helical finned rod under inclined conditions, as follows:

$$CHFR_{IN/VT}^{helical} = f_{gravity}^{helical} - f_{swirl} \quad (3)$$

Where, $f_{gravity}^{helical}$ represents the increase ratio of CHF on helical finned rod due to the component of gravity that is normal to the flow direction and f_{swirl} is decrease ratio of CHF on helical finned rod due to swirl flow.

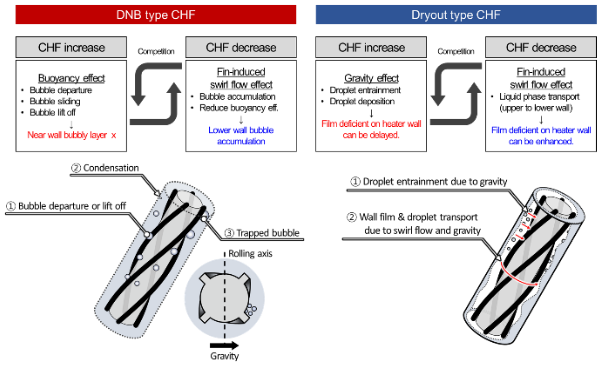

Fig. 4. Increase/decrease mechanism of CHF on helical finned rod in DNB and dryout regimes [5]

The effect of gravity can be assumed to have the same impact on both the bare rod and the helical finned rod ($f_{gravity}^{helical} = f_{gravity}^{bare}$). Hence, the CHF decrease ratio due to swirl flow can be represented as follows:

$$f_{swirl} = f_{gravity}^{bare} - CHFR_{IN/VT}^{helical} \quad (4)$$

The $CHFR_{IN/VT}^{helical}$ was measured experimentally, and $f_{gravity}^{bare}$ can be calculated using the CHF correlations for inclined conditions proposed by Kim et al. Details of the correlations can be found in a previous study [7]. The influence of the swirl flow is anticipated to be a function of the Reynolds number. In particular, in the DNB and dryout type CHF regimes, the Reynolds numbers of the liquid and vapor, which occupy most of the flow area respectively, can be defined as follows:

$$Re_{DNB} = \frac{GD_h(1-x_{eq})}{\mu_l} \quad (5)$$

$$Re_{DO} = \frac{GD_h x_{eq}}{\mu_g} \quad (6)$$

Where, G is the mass flux, D_h is the hydraulic diameter, x_{eq} is the equilibrium quality at the CHF point, and μ stands for dynamic viscosity. The subscripts "l" and "g" denote liquid and vapor respectively. Fig. 5 shows the f_{swirl} along the Re_{DNB} and Re_{DO} for each

CHF regime. As illustrated in Fig. 5, there are regions where f_{swirl} increases and decreases with the Reynolds number. In each CHF regime, the Reynolds number is sufficiently large, allowing it to be considered within the turbulent region. Confirming the two-phase flow regime is challenging due to the complexity of its geometry. Fundamentally, as the Reynolds number increases, the effect of the swirl flow is expected to intensify, as depicted in Fig. 6. However, beyond a certain Reynolds number, streamlines form parallel to the fin, leading to a circumferentially uniform distribution of bubbles or droplets. Consequently, the swirl flow does not impact the $CHFR_{IN/VT}^{helical}$. Shortly, based on the mechanism of CHF on the helical finned rod, the decrease in CHF under the inclined conditions is believed to be the distinct effect of the swirl flow. From the experimental results, a clear trend in f_{swirl} was observed in relation to the Reynolds number, which governs the intensity of the swirl flow.

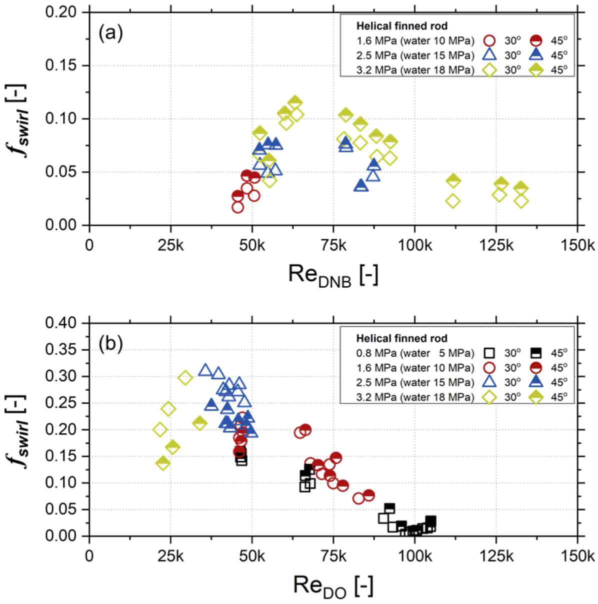

Fig. 5. Swirl flow effect ($\boldsymbol{f_{swirl}}$) versus Reynolds number in each CHF regimes (a: DNB regime, b: dryout regime)

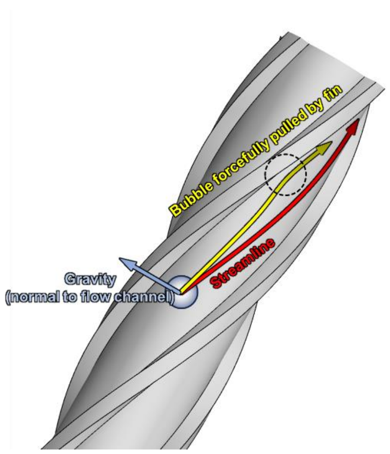

Fig. 6. Schematic diagram of bubble behavior on helical finned heater

4. Conclusion

In this study, the NEOUL-R motion platform was utilized to measure the CHF on a helical finned rod under inclined conditions. Based on the experimental results and the previously proposed inclined CHF correlation for bare rods, the separate effect of the swirl flow was determined. The Reynolds number, in each CHF regime, was identified as the parameter that governs the effect of swirl flow. A clear trend was observed in the effect of swirl flow as related to the Reynolds number. In the future, it is expected that an inclined CHF correlation for helical finned rods will be derived using the separate effect of swirl flow and the Reynolds number.

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