# Effect of Rolling Motion on Pool Boiling Critical Heat Flux (CHF)

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## 1. Introduction

The complex motion of a ship sailing in the ocean is affected the thermal-hydraulic and vapor behaviors of marine reactor. In order to consider the safety margin of marine reactor, it is important to analyze the vapor behaviors and critical heat flux (CHF) under rolling motion.

Most previous studies were experimentally focused on flow distribution, flow instability, and heat transfer. Isshiki [1] conducted series of experiments for both natural and forced circulation under heaving motion. He concluded that CHF decreased with increasing heaving acceleration. Otsuji and Kurosawa [2] studied CHF of forced convection in an oscillating acceleration. They observed an early occurrence of CHF due to the amplitude of inlet flow which induced by the variation of acceleration. They continued their observations [3] and investigate the effect of acceleration variation on CHF in subcooled flow boiling. They found at low gravitational acceleration, vapor generated moved and merged with each other and could not detach easily from the heated surface. This cause an early CHF. Recently, Hwang et al. [4] investigated the characteristic of CHF on flow boiling in a vertical tube under rolling motion. Based on their results, they concluded that the combination of the tangential force and high mass flux contributed to the enhancement of CHF due to the increasing of vapor layer and bubble departure rate. The above previous studies show that research of vapor behaviors and CHF are still needed to elucidate and recognize the factors that triggered CHF under rolling motion. This study is directed at how the rolling motion affected the boiling phenomena and CHF.

## 2. Experimental Facility and Method

A rolling platform system was designed to simulate the ship motion in the ocean. Fig. 1 show the image of the experimental facility. It consists of a rolling platform system, test chamber, a heating jacket, a pre-heater, thermocouple, DC power supply, power meter, current sensor terminal, inclinometer sensor signal, and data acquisition (DAQ) system.

The test chamber made of Aluminum was filled with deionized water. A pre-heater (100W) was installed to heat the water up to the saturation condition. A K-type thermocouple was inserted to monitor the bulk temperature. In order to minimize the heat losses from the surrounding, the test chamber was covered with a heating jacket (250W). To monitor the heat supplied to the wall of test chamber through the heating jacket, another K-type thermocouple was placed between the test chamber and heating jacket. A digital high-speed camera was used to record the boiling phenomena during the experiment. A halogen backlight was placed at the back of the test chamber to have better image and video. The high-speed camera was set 1000 ppm of rate with the resolution 800 × 600 pixels. A reference probe was installed and easily converted the size from pixel to mm.

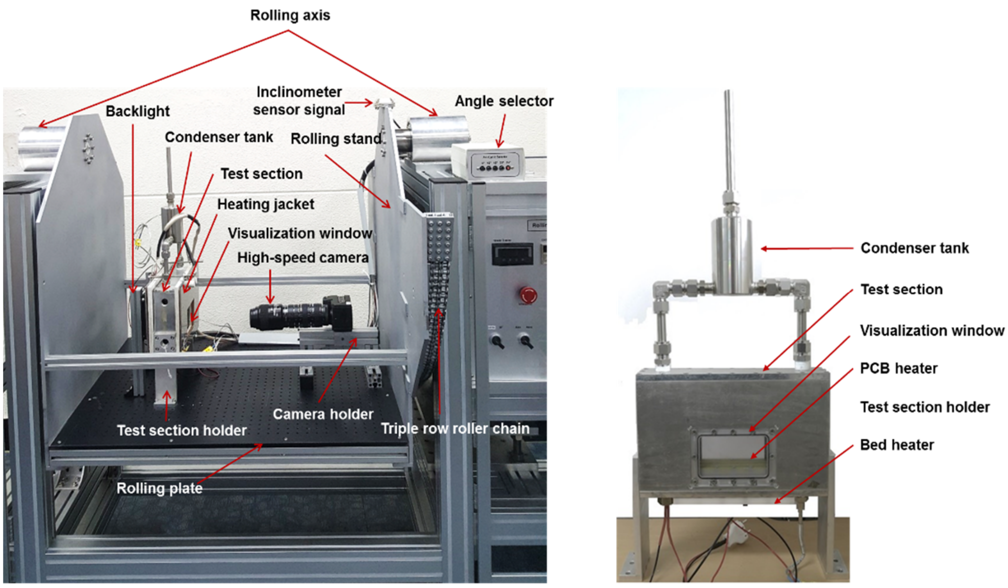


Fig. 1 Image of test section and rolling platform system

A rectangular copper heater was printed on the circuit board as shown in Fig. 2. To monitor the exact power supplied to the heater, DC power supply was connected with the power meter by using the current sensor terminal [5-7].

To have a uniform surface condition, the copper surface was treated. The surface was polished by sandpaper and alumina powder. The polished surface was cleaned by water and acetone. To prevent the onset of moister on the surface, the surface was dried by oven for 10 minutes at 50˚C. The dried copper heater was sealed in a vacuum bag. In this study, the surface condition was stabilized at approximately 0.1 µm of surface roughness checked by atomic force microscopy (AFM) machine and approximately 82˚ of contact angle measured by a sessile drop technique.

The test chamber, high-speed camera, and backlight were placed on the 800 × 900 mm of rolling platform. The rolling platform was driven by a servo motor with thirteen sensors placed precisely to monitor the maximum rolling amplitude. The rolling period was controlled by the speed of the platform. The rolling amplitude and period was set as the ship sailing in on the ocean. The experiment begin as the water at saturation temperature and the platform switched on. By increasing the power gradually, the vapor behaviors were observed until it reached the CHF. In this study, CHF was defined as the burned out occurred on the heated surface. Table 1 summarizes the experimental parameters and conditions.

Table 1 Experimental parameters and conditions

| Parameter | Condition |
|---|---|
| Maximum rolling amplitude | 10, 20 and 30˚ |
| Rolling period | 10 and 15 second |
| Bulk temperature | 100 ˚C |
| Surface roughness and wettability | ± 0.1 µm and ± 82˚ |

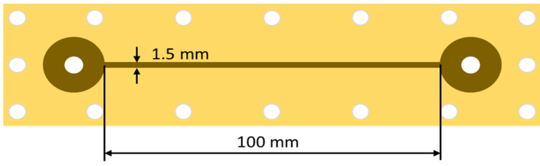


Fig. 2 Schematic of PCB heater

### 3. Results and Discussion

Fig. 3 depicts the sequence of vapor behaviors with increasing heat flux under static and rolling conditions. Under static condition, the sequence of boiling phenomena was observed at horizontal facing upward (at 0˚ angle), while under rolling motion, the phenomena captured at the maximum rolling amplitude of each cases (at 10, 20, and 30˚ angle). As shown, the generated bubble grew and drifted along the heated surface as the platform rolls. The motion leads the bubble to stay longer on the heated surface without detachment. As the heat flux increased, the bubble grew bigger and coalesced with each other and formed bigger bubble which occupied wider area on the heated surface. As the platform rolls, the oscillation helps the bubble to merge with neighboring bubble. It was observed that the nucleation site density was easily activated, resulting in the reduction of length between bubbles. The evaporation increased as the platform rolls faster. This phenomenon leads the bubble to merge and grew bigger and formed a vapor film on the heated surface. At the same time, additional accelerations acted to push the bubble and could not detach easily from the heated surface. The combination of accelerations (gravity, tangential and centrifugal) that acted on the platform, affected the vapor behaviors every time the platform rolls up and down as shown in Fig 4. Chaotic oscillation becomes greater as the maximum rolling amplitude increased. The shrinkage of the vapor caused by buoyancy and additional forces driven large coalesced bubble rising on the heated surface. The fluid penetration following the dry spot shrinkage due to the rising vapor that almost simultaneously accompanied the formation of new dry spot and their merging to rapid evaporation. These phenomena significantly interrupted the fluid to replenish the heated surface, resulting in the occurrence of CHF. As the maximum rolling amplitude increased, the occurrence of CHF becomes faster. Early CHF occurred at highest maximum rolling amplitude [4].

Under rolling motion, CHF and CHF ratio were affected by the maximum rolling amplitude and period as displayed in Fig. 5. CHF ratio was the comparison between $CHF_{rolling}$ and $CHF_{static(0^{\circ})}$. CHF and CHR ratio decreased with increasing the maximum rolling amplitude due to the rolling motion induced flow oscillation which caused the heat transfer deteriorated. CHF and CHF ratio were enhanced with increasing the rolling period. The faster the platform rolls, the lower the CHF and CHF ratio, and in the vice versa.

### 4. Conclusions

Effect of rolling motion on vapor behavior and CHF in a saturated water pool was experimentally investigated. Major findings from this study are as follows;

- The rolling motion provokes the flow distribution and thermal stratification of the fluid which lead to the deterioration of heat

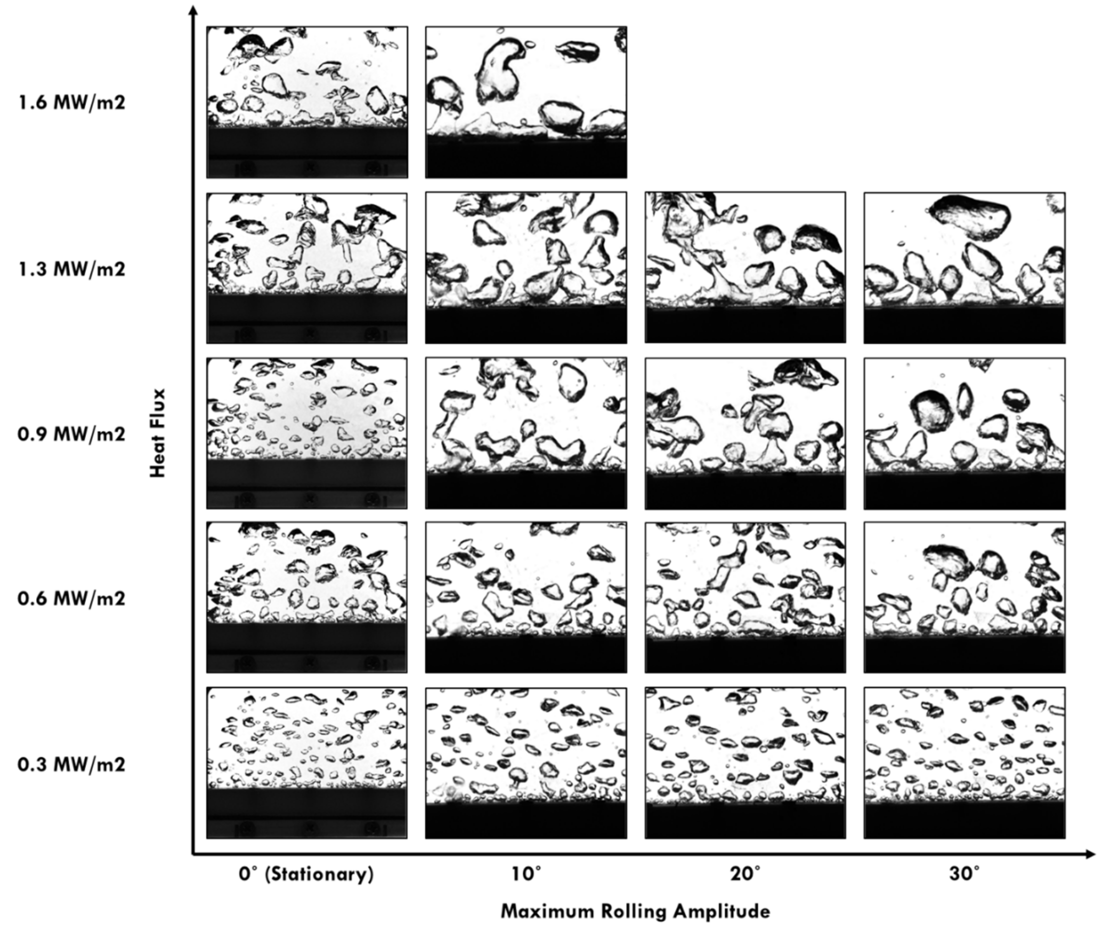


Fig. 3 Image of vapor behaviors with increasing heat flux at various maximum rolling amplitude (period 15 Sec)

transfer coefficient.

- The oscillation and additional accelerations acted on the platform keep the bubble to grow and coalesced with each other without detachment. The heated surface was covered with a great bubble for longer time and prevented the fluid to replenish the heated surface. This phenomena resulting in the occurrence of CHF.

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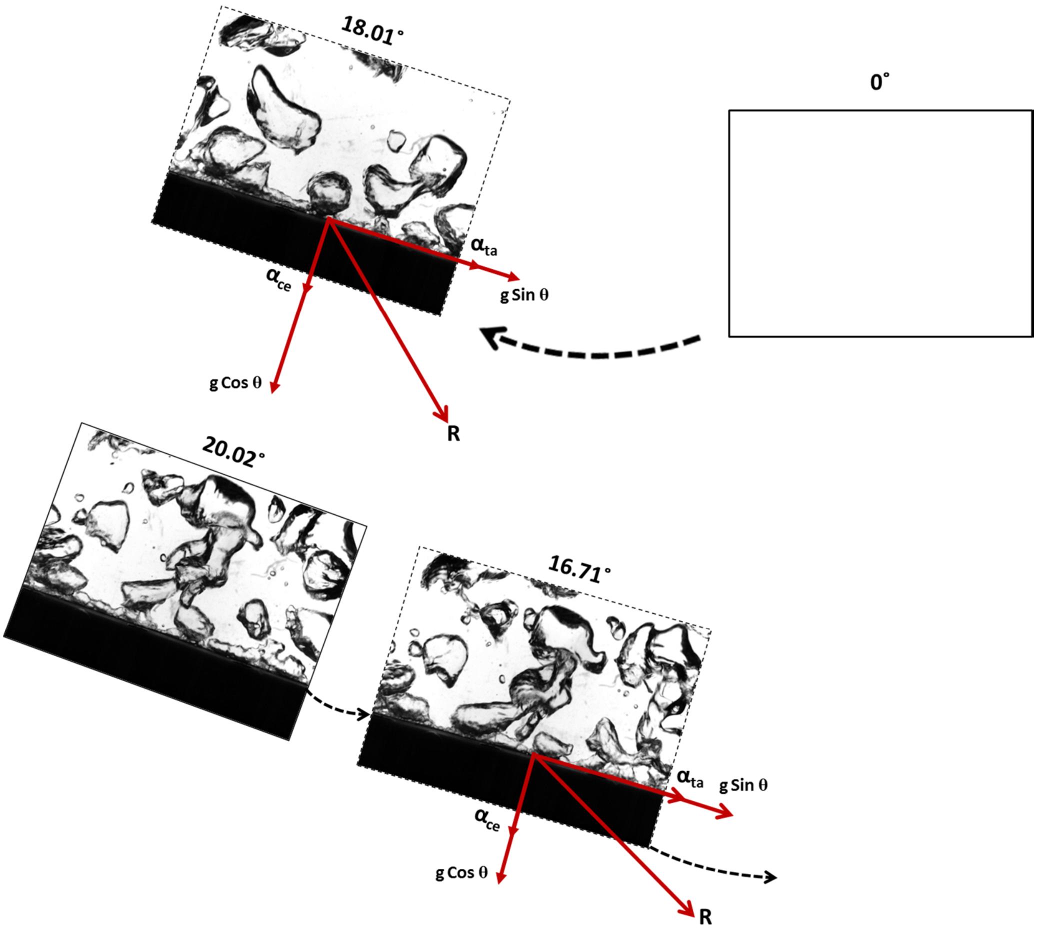


Fig. 4 Detailed of vapor behaviors as the effect of additional accelerations when the platform rolls up and down (at A = 20˚, and T = 15 Sec)

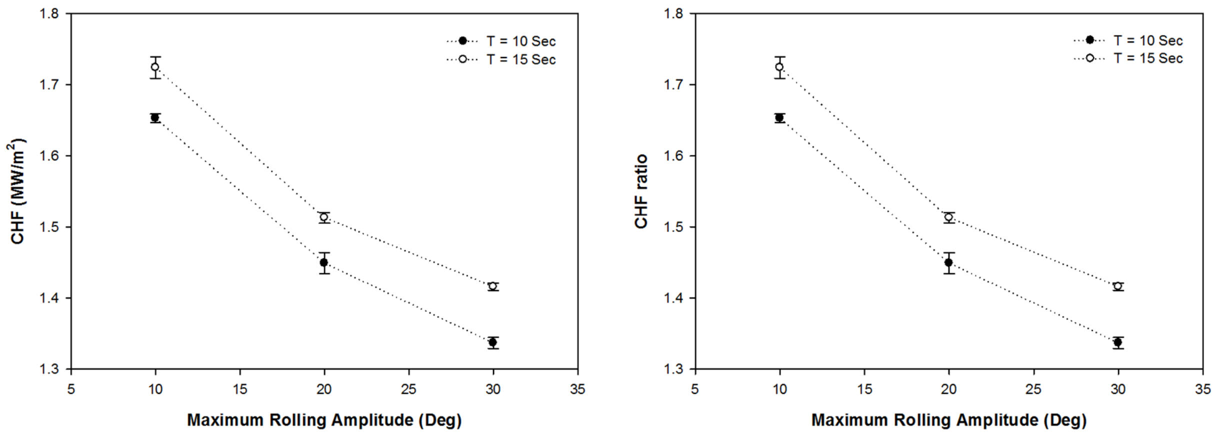


Fig. 4 Effect of rolling motion on CHF and CHF ratio