Bubble Phenomena and Critical Heat Flux (CHF) from Horizontal, Vertical, and Inclined Surfaces in a Saturated Pool

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1. Introduction

Pool boiling at various heater orientations is essential for the efficient operation, safety and development of nuclear reactors since it has significant effects on boiling process. Bubble phenomena: bubble growth, merger and departure processes are critical parameters for nucleate boiling.

Previous investigations indicated that bubble departure diameter and nucleation site density increased as the heater surface is placed horizontally facing upward at 0˚ angle to vertical at 90˚ angle [4]. Kim et al. [3] experimented in a pool filled with demineralized water as their working fluid and copper block as the heater. They investigated that the approximate bubble diameter and overall size in the upward heater surfaces are slightly larger than those in the downward heater surfaces.

Nishikawa et al. [5] observed remarkable effect on the low heat flux as the heater orientation increased, while no marked effect at high heat fluxes. Rainey and You [6] investigated the effects of heater size and orientation on pool boiling heat transfer. The critical heat flux (q_{CHF}) decreased with increasing heater size and orientation angle.

The aim of present study is to investigate the bubble phenomena and CHF from horizontal, vertical, and inclined surfaces in a saturated pool. Furthermore, the pool boiling phenomena at 0˚, 45˚, 90˚, 135˚, and 180˚ orientation angles will be recorded with a high-speed camera to give better understanding of the bubble phenomena.

2. Experimental Apparatus

Pool boiling experimental setup is shown in Fig. 1. The test section is made of Aluminum with the overall dimensions of 260 mm x 160 mm x 60 mm. Two polycarbonate visualization windows were held in place by laterally compressing the assembly with a set of M4 fasteners.

A single plate of PCB heater made by copper with a length of 100 mm, and a width and thickness of 1.5 mm and 50 μm respectively is shown in Fig. 2(a). The copper heater was polished with sand paper and Alumina powder to have a uniform surface condition in every experiment. The roughness average of the PCB heater was checked by the atomic force microscopy (AFM) which measured ± 0.1 μm. Moreover, using a sessile drop method, the PCB heater surface wettability was measured ± 81.9˚ and compared with previous studies. Zhang et al. (1984), Ponter et al. (1985) and Exterand et al. (2003) investigated the contact angle of droplet water on a copper surface were 71˚, 78˚ and 69˚ respectively while Lee (2015) measured 81.05˚. The heater surface in the present work shows a hydrophilic surface with $0˚ < \theta < 90˚$ which means has a high wettability [10]. Figure 2(b-c) showed the surface roughness and wettability of the PCB heater.

The test section was filled with de-ionized water and heated up to the saturated temperature by a preheater. Once it reached the saturation temperature, the preheater was turned off, and the heating jacket (250W) was turned on to maintain the fluid in saturation temperature. A K-type sheathed thermocouple was placed 25mm horizontally apart from the edge of the PCB heater to monitor the bulk temperature. Another K-Type sheathed thermocouple was placed on the heating jacket to control the heating jacket temperature.

A DC power supply with the voltage range of 0-10 Volt and current range of 0-100 Ampere was used to supply the power to the PCB heater. The DC power supply was connected to a power meter by a current sensor terminal to get the exact power that was supplied to the PCB heater.

A high-speed camera (MIRO EX4) with 800x600 pixels was used to record the bubble phenomena during

Table I: Correlations of Pool Boiling CHF

Reference	Correlation
Vishnev (1974) [2]	$\frac{q''_{CHF}}{q''_{0°}} = \frac{(190-\theta)^{0.5}}{190^{0.5}}$
El-Genk and Guo (1993) [8]	$q''_{CHF} = 0.034 + 0.0037\,(180-\theta)^{0.656}\,\rho_g\,h_{fg}\left[\frac{\sigma(\rho_f-\rho_g)g}{\rho_g^2}\right]^{1/4}$
Brusstar and Merte (1994) [9]	$\frac{q''_{CHF}}{q''_{0°}} = \begin{cases} 1.0 & 0° < \theta \le 90 \\ (\sin\theta)^{12} & 90° \le \theta < 180 \end{cases}$
Arik and Bar-Cohen (2001) [7]	$\frac{q''_{CHF}}{q''_{0°}} = 1 - 0.001117\,\theta + 7.79401 \times 10^{-6} \times \theta^2 - 1.37678 \times 10^{-7} \times \theta^3$

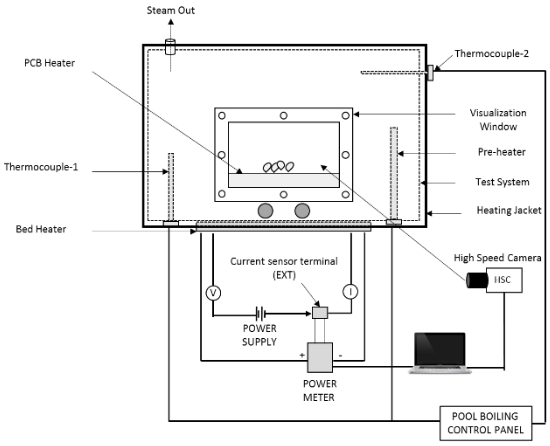
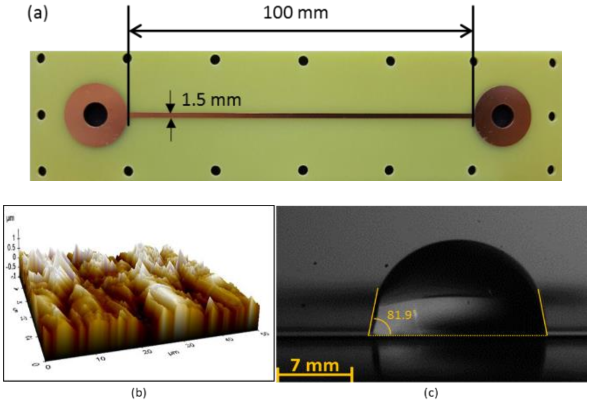


Fig. 1 The schematic diagram of pool boiling experimental setup.



(b) (c)

Fig. 2 (a) The schematic diagram of PCB heater; The PCB heater surface condition (b) Roughness, and (c) Wettability.

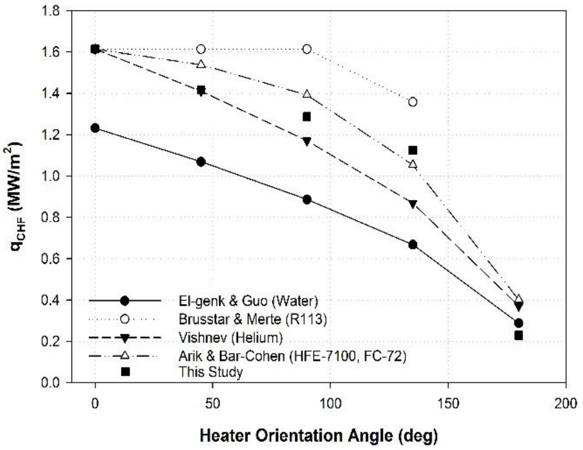


Fig. 3 Comparison of existing CHF data with some correlations at various heater orientation angles.

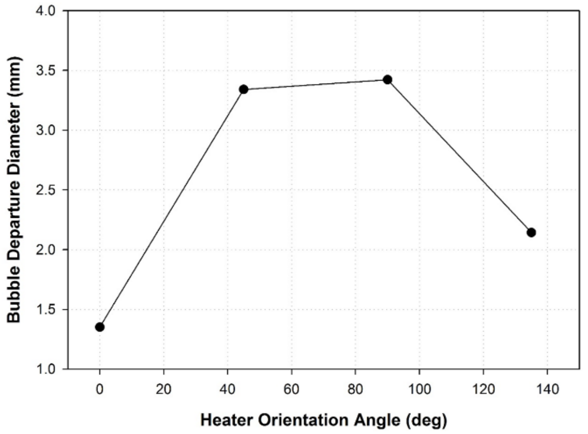


Fig. 4 Bubble departure diameter at various heater orientation angles.

the experiment. Afterward, all the recorded videos are converted into photo file using the PCC 2.6 software, then image processing was performed using an image analysis software (Matlab 2015). The data in this experiment was automatically saved to the personal computer by using PCC 2.6 and WTViewer.

3. Results and Discussion

3.1 Effect of Heater Surface Orientation on CHF

In the present study, bubble phenomena and CHF on the PCB heater at various angles were investigated. The 0˚ orientation angle (horizontal facing upward) was used as the reference among the other four orientation angles. Figure 3 shows the effect of heater surface orientation angle on CHF. The present data was compared with the correlations that are summarized in Table I. As illustrated in Fig. 3, the CHF decreased with the increasing heater surface orientation from 0˚ to 180˚ orientation angles. The present study showed a good agreement with the results calculated using the correlations in Table I. Vishnev [2] was the first researcher to correlate the effect of heater orientation angle on the pool boiling CHF. He used a flat disk heating surface and helium as the working fluid. El-Genk and Guo [8] make another correlation for the CHF at various heater orientation angles based on their experimental data. Brusstar and Merte [9] predicted the heater orientation effect on R113 with the heater surface orientation $\theta < 165˚$. Arik and Bar-Cohen [7] proposed a correlation based on the working fluid of mixed liquid (HFE-7100 and FC-72). The results gap illustrated in Fig. 3 are possible due to some differences in the heater geometry, material, surface roughness, wettability, and also the working fluid used in their studies.

3.2 Effect of Heater Surface Orientation on Bubble Size

For the analysis of bubble departure diameter, more than 5,000 images were processed using Matlab 2015. Figure 4 shows the bubble departure diameter at various heater orientation angles. The basic image processing functions were used to analyze the bubble departure

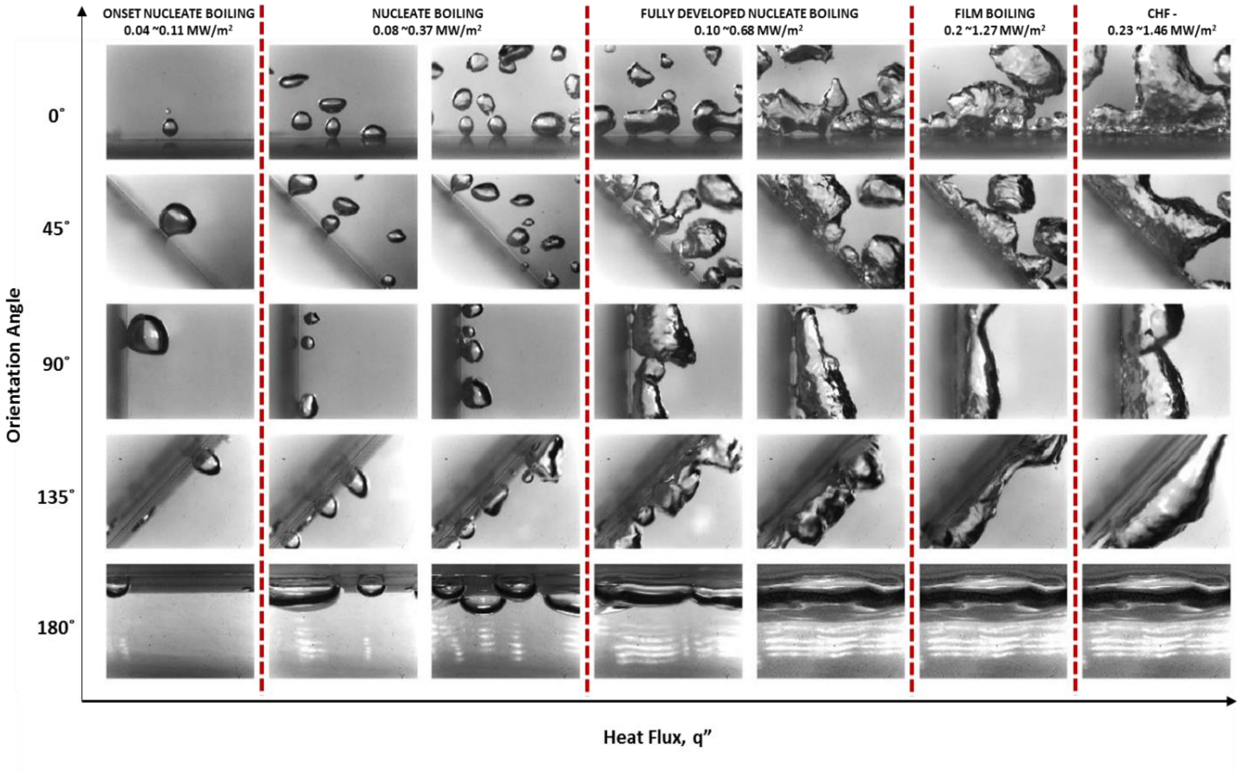


Fig. 5 Snapshot of bubble phenomena on PCB with increasing heat flux at various heater orientation angles.

diameter. In this study, the bubble departure was assumed in a spherical shape. An algorithm was used to measure the sauter mean diameter of the departure bubble.

The bubble departure diameter increased with the increasing heater orientation angle from 0˚ to 90˚ orientation angles and tend to decrease as the heater orientation faced downward at 135˚ orientation angle. Similar results were observed by J. Satbyoul and H. Kim [4], and Kim et al. [3]. The bubble generated at the heater surface orientation facing upward tend to detach easily from the heated surface by the buoyancy, while the movement in bubble generated from the heater at 135˚ and 180˚ orientation angles were restricted by geometrical location due to gravity [3]. On the other hand, bubble departure diameter at 180˚ orientation angle is not measured in this study because the generated bubble did not detach from the heated surface.

3.3 Effect of Heater Surface orientation on Bubble Phenomena

Figure 5 shows the bubble behaviors on the PCB with increasing heat flux at various heater orientation angles. At very low heat flux with the heater at 0˚ and 45˚ orientation angles, the bubble generated is growing before it detaches in the vertical direction to the heated surface. The nucleation sites also became active and generate more bubbles as the heat flux increase. The generated bubbles initially coalesced with each other and formed an elongated bubble as the heat flux increased slowly. At the fully developed nucleate boiling region, the elongated bubble interacted with each other to form a huge bubble with irregular shape. The vapor film formed at very high heat flux tend to cover the heated surface and impede the incoming water from having contact with the heated surface causing to reach the CHF at 1.6 MW/m^2 and 1.4 MW/m^2 for heater surface orientation of 0˚ and 45˚ respectively.

At 90˚ orientation angle, the bubble generated at very low heat flux is drifted along the surface before it detached when it reached a certain size. An elongated bubble formed mostly because of the successive generation of bubble on the heated surface. Wavy vapor film is formed as the result of the interaction of elongated bubble as the heat flux is increased. The wavy vapor film became thicker and drifted along the heated surface continuously. This behavior delayed the period of stay of the wavy vapor film and hindered the liquid to have contact with the surface, and the CHF occurred at 1.2 MW/m^2.

On the other hand, at 135˚ orientation angle, at the low heat flux, bubble generated and drifted along the surface before it detached at the most upper part of the PCB heater. The bubbles coalesced with each other and formed an elongated bubble as the heat flux increases. At the fully developed nucleate boiling region, a thin wavy vapor is formed and drifted along the heated surface. The wavy vapor became thicker at the very high heat flux. The agitation on the fluid increases the peak of the heat flux through the reduction of the period of stay of the wavy vapor, resulting to early CHF at 1.1 MW/m^2.

In contrast, when the heater was placed at 180˚ orientation angle, the generated bubble stayed on the heated surface. As the heat flux increased, the nucleation sites became active and generated more bubble. The generated bubbles from the nucleation sites that are close to each other caused the bubbles to coalesced until the entire heated surface was covered by the vapor film. The CHF occurred at 0.2 MW/m^2 earliest among those other four heater orientation angles as a consequence of the vapor film that covered the heated surface hindering the liquid to have contact with the heater surface.

3. Conclusions

Series of experiments to investigate the bubble phenomena and CHF from horizontal, vertical and inclined surfaces in saturated pool were conducted. Several conclusions derived from this study are as follows;

1. The CHF decreased with the increasing heater orientation from 0˚ to 180˚ angles. The maximum heat flux observed at 0˚ orientation angle is 1.6 MW/m^2, and decreased to 1.4 MW/m^2, 1.2 MW/m^2, 1.1 MW/m^2 with the minimum CHF of 0.2 MW/m^2 at 45˚, 90˚, 135˚, and 180˚ orientation angles respectively. The CHF data in the present study showed a good agreement with the correlations proposed by previous studies [2, 8. 9, 7], which confirm that CHF is a strong function of heater orientation angle.
2. In the upward facing orientation (at 0˚ and 45˚ angles), the buoyancy forces eliminated the vapor from the heater surface vertically. At vertical heater orientation, the wavy vapor drifted along the heater surface. As the heater placed facing downward at 135˚ and 180˚ orientation angles, the wavy vapor laminated the entire heater surface continuously, greatly decreasing the CHF.
3. The behaviors of the bubble at various angle affected the bubble departure diameter. The bubbles that generated on the heater facing downward could not escape freely from the heated surface, the presence of the solid heater leads the bubble to drift upward before it detaches. For this reason, the bubble departure diameter on the heater facing downward is smaller compared to heater facing upward.

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