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Pool-Boiling Critical Heat Flux of Water on Small Plates: Effects of Surface Orientation and Size

Soo-Hyung Yang, Won-Pil Baek and Soon Heung Chang

Department of Nuclear Engineering
Korea Advanced Institute of Science and Technology

ABSTRACT

The pool-boiling critical heat flux (CHF) of water on small flat plates has been experimentally investigated focusing on the effects of the inclination angle and size of the heated surface under near atmospheric pressure. The second-phase experiment was accomplished to find out the general CHF behavior for overall inclination angles from -90° to 90° using two plate-type test sections (30×150 mm and 40×150 mm) submerged in a slightly subcooled water pool. Test results generally confirm the first-phase findings and show little effect of inclination angle for inclined upward-facing cases. CHF position moves to lower position with the increase of the heater characteristic size and inclination angle(from -30° to 60°).

1. INTRODUCTION

The pool-boiling CHF has been extensively investigated during the past few decades. Significant amount of experimental work with discs, cylinders, upward-facing and vertical plates has made a great progress in understanding this complicate phenomenon in several aspects: the physical mechanisms leading to the CHF, effects of various system parameters, etc. In particular, the CHF condition on an infinite horizontal upward surface is well explained by a hydrodynamic instability model [1] or a macrolayer dryout model [2]. Recently, pool-boiling CHF phenomena for somewhat unusual conditions are highlighted with respect to practical applications. One of them is the CHF on a downward-facing plate or curved surface, which is related to the cooling of reactor vessel lower head during a severe accident or the cooling of electronic equipment. However, relevant experimental works are scarce and the physical mechanisms leading to the CHF are not well understood. This leads to the lack of reliable prediction models. Therefore, there is a strong need for much more work to clarify the CHF mechanisms and to develop prediction models for these configurations.

A series of CHF tests is being conducted for small flat plates submerged in a pool of water, with varying the size and inclination angle of heated plates and cooling water conditions. This paper presents the results of second phase experiment performed with two different test sections.

2. PREVIOUS WORKS

Githinji et al. [3] obtained the boiling curve for 3 different surface inclination angles (-90°, 0° and 90°) using a 1/8-inch-width strip in a subcooled pool of 80°F isopropyl alcohol under atmospheric pressure. They showed that the boiling curve for the horizontal downward-facing surface was different from those for the other inclinations and the CHF was considerably lower for the downward-facing surface. They also suggested that the CHF on the vertical surface was higher than that on the horizontal upward-facing surface. Anderson et al. [4] performed the boiling heat transfer experiment of Freon-11 with downward-facing discs of diameters from 2 inch to 2 feet. They reported that the CHF was a strongly decreasing function of diameter and slight deviations from horizontal position (up to 15 degree) had little effect on the CHF. Vishnev et al. [5] performed CHF tests for helium pool and found that the CHF decreased as the surface inclination was varied from upward to downward. They suggested a correction factor to represent the surface inclination effect on the CHF:

$$q_c(\theta) = z(100+\theta)^{0.5} h_{fg}\left[\eta g\sigma(\rho_f-\rho_g)\rho_g^2\right]^{0.25} \tag{1}$$

where $z = 0.0125$ and θ is the inclination angle measured from the vertical position.

Yang et al. [6, 7] performed pool boiling CHF experiment for inclined plates using two plate-type test sections submerged in a pool of saturated water under atmospheric pressure. They reported that the CHF decreased with increase of heated surface width and decrease of inclination angle due to the increased difficulty for the bubbles in escaping from the heated surface. They suggested a transition angle (θ_{tr}), at which the decrease rate in the CHF is suddenly changed. According their experimental data, the angle was observed in the vicinity of -80°.

El-Genk et al. [8-10] performed an extensive experimental study on CHF with downward-facing flat and curved surfaces with thick wall using the quenching method. They obtained the pool-boiling curve of water on a downward-facing copper disc of 12.8-mm thickness and 50.8-mm diameter [8, 9]. They also performed tests with curved downward surface (12.8 and 20.0-mm thickness, 50.8-mm diameter and 148-mm surface curvature radius) [10] to investigate the inclination angle effect. The following CHF correlation for inclined surfaces was proposed based on the data of El-Genk et al. and others [9]:

$$q_c(\theta) = C(\theta) h_{fg}\rho_g^{1/2}\sqrt[4]{g\sigma(\rho_f-\rho_g)} \tag{2}$$

where $C(\theta)$ is function of inclination angle and fluid property.

Theofanous et al. [11, 12] also performed the CHF tests with the large curved surface. The CHF was found to be an monotonously increasing function of the inclination angle, contrary to the results of El-Genk et al. They suggested the following correlation based on the data obtained from ULPU Configuration II facility:

$$\begin{aligned} q_c(\theta) &= 500+13.3(\theta+90) \quad \text{kW/m}^2 \quad \text{for } \theta < -75^\circ \\ &= 540+10.7(\theta+90) \quad \text{kW/m}^2 \quad \text{for } -75^\circ < \theta < 0^\circ \end{aligned} \tag{3}$$

Equations (1)-(3) ignore the heater size effect that could be important in downward-facing plates. However, Granovskii et al. [13] included the size effect in their correction factor for the CHF on horizontal downward-facing surfaces:

$$\frac{q_c(-90^\circ)}{q_c(90^\circ)} = \begin{cases} (1.24/D^*)^{3/10}, & 2 \le D^* \le 48 \\ (12.8/D^*)^{5/6}, & D^* > 48 \end{cases} \tag{4}$$

3. EXPERIMENT

3.1 Experimental Apparatus

The second-phase experiment was accomplished to find out the general CHF behavior for overall inclination angles. Somewhat different test loops, compared to first-phase experiment, were used for the second phases as shown in Fig. 1. A larger test pool (600×600×900 mm) was made up of Type-304 stainless steel except for the front and back parts for the same reason as the first-phase experiment. The inclination angle of the heated surface was provided by fastening the test section to the electrode positions installed at the side parts of the test pool. Fig. 2 shows two test sections used in the second phase experiment. Overall configurations are similar to those for the first-phase experiment. A new 40 V, 5000 A DC power supplier was used and the temperature of the heated plate was measured by five Type-K thermocouples embedded at the wall contacting with water. The test section power, heated plate temperatures and pool water were processed by a data acquisition system, consisting of a HP Series 300 workstation, a HP 3852A data acquisition/control unit and an IBM PC/486. Experimental errors involved in the temperature measurement were estimated to be ±1.6°C and ±1.5°C for Type-K and Type-T thermocouples, respectively. The error involved in the angle measurement was estimated to be about 0.5 degree.

3.2 Test Method and Ranges

The test section dimensions and test ranges of second-phase experiments are summarized in Table 1. CHF was measured for -90°, -60°, -30°, 0°, 30°, 60° and 90° using T/S-3 (30×150 mm) and T/S-4 (40×150 mm). The pool water was maintained at slightly subcooled condition under near atmospheric pressure. Every effort was made to maintain the heated surface at clean condition for all runs and a selected number of repeated tests were performed for the same test condition to assess the reproducibility of the CHF data. In the present tests, the CHF condition was practically defined as the condition that maximum wall temperature increased continuously and exceeded 250°C. This was because preliminary tests indicated that the wall temperature increased abruptly to above 400°C once it exceeded about 250°C.

4. RESULTS AND DISCUSSION

4.1 Overall Behavior and Parametric Trends

Tables 2 summarizes the CHF data measured in the present work. Figure 3 shows the data in comparison with the data by El-Genk et al.[8] and predictions for an infinite upward plate [1, 14]. As the second-phase experiments were accomplished under slightly subcooled condition, the measured CHF data in T/S-3 and T/S-4 are converted to CHF values for saturation condition using Ivey and Morris correlation for subcooled CHF [15], assuming the same subcooling effects for all inclination angles. Overall observations of the present work can be summarized as follows:

- The general CHF behavior observed for downward face in the first-phase experiment is confirmed: increase of CHF with the inclination angle, the lower CHF for wider test section, a steep decrease of CHF near -90°, much smaller effect of orientation for $\theta > \theta_{tr}$, etc. The transition angle could not be exactly defined, however, it may be located between -60° and -90°.
- The effect of surface orientation and heater characteristic size on CHF becomes unclear for upward surfaces ($0^\circ < \theta < 90^\circ$). However, the CHF position moves to lower position with the increase of the heater characteristic size and inclination angle (from to -30° to 60°).

4.2 Visual Observation

Description of the bubble behavior on large heated surface is scarce in the literature; therefore, the observed behaviors of bubbles near the heated surface are described. The bubble behaviors for horizontal downward surface and inclined downward surface are similar to those of the first-phase experiment [6, 7]. In this paper, specially, the behaviors for vertical position are mainly described, including the pictures as shown in Fig. 4.

Vertical surface

At very low heat fluxes (below about 50kW/m^2), the bubbles generated at the nucleation site move upward along the heated surface without significant coalescence, as shown in Fig. 4(a). As heat flux increases, the coalescence of bubbles moving upward becomes significant and large bubbles escape mainly through the top edge. A cyclic phenomenon is observed as shown in Fig. 4(b): (a) formation of a large coalesced bubble in the lower part of the heater plate, (b) rise of the large bubble along the surface, and (c) the escape of the large bubble through the top edge and initiation of another large coalesced bubble. The period of this cyclic behavior decreases with the increase of heat flux up to the CHF point (Table 3).

Horizontal upward surface

At low heat fluxes, the bubbles generated at heated surface coalesce with surrounding bubbles and escape along the center line of heated surface. As the heat flux increases, bubbles escape from the entire heated surface. However, it was difficult to clearly observe the bubble behaviors on upward surfaces due to the limitation of our facilities.

4.3 Effects of Inclination Angle and Heater Size

Figure 3 shows that Eqs. (1)-(3) which are applicable to their experimental data cannot adequately predict the CHF data measured in present work. Though several other parameters, such as the thickness and material of heated surface, coolant condition, may also affect the CHF, the major reason for disagreement would be the ignorance of the size effect in those correlations. The size effect would not be so important for upward surfaces of characteristic sizes around several centimeters. However, for vertical and downward surfaces where the bubble escape is considerably difficult and dependent on the neighboring bubble, the size effect would be still important for these sizes. The threshold characteristic size above which the size effect becomes negligible, if exists, would be much larger for downward surfaces compared with those for upward or vertical surfaces.

From the viewpoint of the difficulty in bubble escape, the width of a plate heater and the diameter of a disc heater can be used as the characteristic size. Equation (4) has been tested with the measured CHF data for -90°. When Zuber correlation [1] is used for the upward CHF, Eq. (4) underestimates the data of T/S-1 and T/S-3 by 18.8% and 4%. However, it overestimates the data of T/S-2, T/S-4 and Guo & El-Genk by 16.8%, 9.2 and 225%. According to these results, the size effect is much more significant than considered by Granovskii et al. as characteristic length increases.

5. CONCLUSIONS

In this work, an experimental study has been performed to investigate the effects of the heated surface orientation and size on the pool-boiling CHF of near-saturated water under atmospheric pressure. Important findings are summarized as follows:

1. For downward plates, the CHF decreases with the increase in the heater characteristic size and with the decrease in the inclination angle. This can be attributed to the increased difficulty of bubble escape for the wider test section. The size effect becomes more important as the inclination angle approaches to -90°.
2. As the inclination angle of heated surface changes from vertical to horizontal downward-facing position, the CHF decreases gradually until a transition angle. The CHF decreases sharply after that angle. The transition angle is around -80° for the test sections of first-phase experiment, but seems to be an increasing of the heater characteristic size. Second-phase experiment also confirms the existence of transition angle between -60° and -90°.
3. For upward plates, the effect of heater surface orientation and size is small or negligible compared to that of downward plates, however, the CHF position moves to lower position with inclination angle.

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NOMENCLATURE

D	diameter of the heated disk, m
D^*	dimensionless diameter, D/λ
g	gravitational acceleration, m/s^2
h_{fg}	latent heat of vaporization, J/kg
K	constant in the pool-boiling CHF correlation
q_c	critical heat flux, kW/m^2
λ	Taylor wavelength scale, $\lambda=(\sigma/g\Delta\rho)^{0.5}$, m
θ	inclination angle (+90° for a horizontal upward-facing plate, 0 for a vertical plate, and -90° for a horizontal downward-facing plate)
θ_{tr}	transition angle, degree
ρ_f	liquid density, kg/m^3
ρ_g	vapor density, kg/m^3
$\Delta\rho$	density difference between phases, $(\rho_f - \rho_g)$, kg/m^3
σ	surface tension, N m/s
η	overload factor

Table 1. Test Matrix of the second phase experiment

	-90°	-60°	-30°	0°	60°	90°
T/S-3 (30×150×2)	T3_-90	T3_-60	T3_-30	T3_0	T3_60	T3_90
T/S-4 (40×150×2)	T4_-90	T4_-60	T4_-30	T4_0	T4_60	T4_90

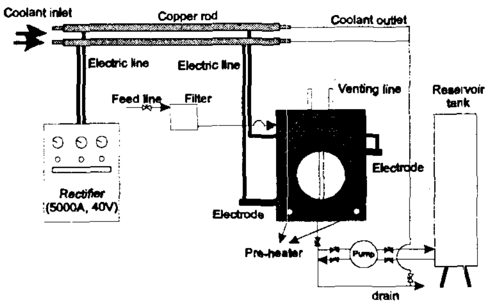
Table 2. Summary of Second-Phase Experimental Results

Incl. Angle		T/S-3		T/S-4		CHF Ratio	
(deg)	Meas. CHF	Avg. CHF (a)	RMS (%)	Meas. CHF	Avg. CHF (b)	RMS (%)	$\frac{(a)-(b)}{(a)}$
-90	578 604	591	0.8	462 476	469	1.5	0.21
-60	1092 1074	1083	0.8	1026 980	1003	2.3	0.07
-30	1124	1124	-	981 1025	1003	2.2	0.11
0	1194 1166	1180	1.2	1056 1103	1080	2.2	0.08
60	1173 1188	1181	0.6	1156 1197	1177	1.7	0.004
90	1114 1125	1120	0.5	1132	1132		- 0.011

$$* : \text{Error} = \sqrt{\sum_{i=1}^{n}(x_i - x_{avg})^2 / n}$$

Table 4. Duration time for each cycle

Heat flux (kW/m^2)	Duration time for each cycle (sec)
131	0.0908
282	0.082
329	0.0768
567	0.0718



b) Second Phase Experiment

Fig. 1 Schematic Diagram of the Pool Boiling Experimental Loops

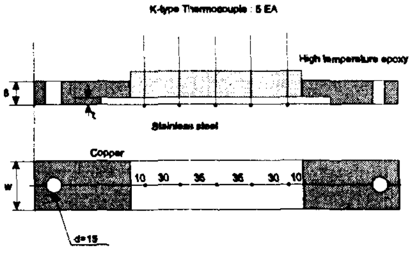


Fig. 2 Schematics of the Test Sections (unit: mm)

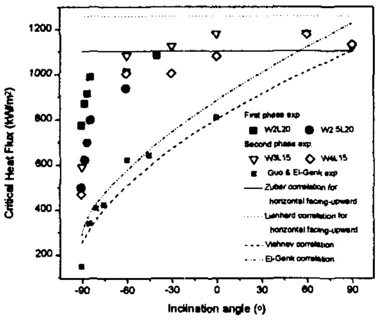
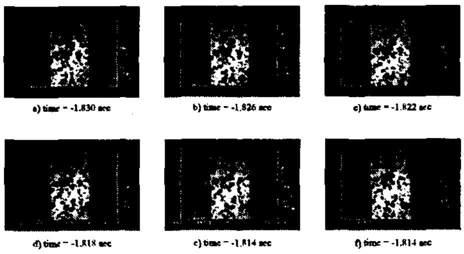
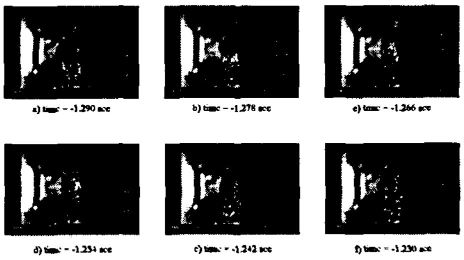


Fig. 3 Overall Behavior of the CHF



a) time = -1.830 sec
b) time = -1.826 sec
c) time = -1.822 sec
d) time = -1.818 sec
e) time = -1.814 sec
f) time = -1.814 sec

a). Low Heat Flux



a) time = -1.290 sec
b) time = -1.278 sec
c) time = -1.266 sec
d) time = -1.254 sec
e) time = -1.242 sec
f) time = -1.230 sec

b) High Heat Flux

Fig. 4 Bubbles Behavior at the Vertical Surface