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An Experimental Study of the Pool-Boiling CHF on Downward-Facing Plates

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하향 평판에서의 풀비등 임계열유속에 관한 실험적 연구

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Abstract

An experimental study has been performed on the pool-boiling critical heat flux (CHF) phenomenon on downward-facing plates. The CHF for inclinations of -90°(horizontally downward position), -88°, -86°, -84°, -60° and -40° were measured using plate-type test sections of 20mm 200mm and 25mm 200mm in a pool of saturated water under atmospheric pressure. The measured CHF was lower for the wider test section and decreased as its orientation approached to the horizontally downward position. The lower CHF can be attributable to the increased difficulty for the bubbles in escaping from the heater surface. When compared with the previous works, the overall trends were similar; however, a transition angle, at which the decrease rate in the CHF was changed, was observed in the vicinity of -80°.

요 약

하향 가열 평판에서의 풀비등 임계열유속 실험이 수행되었다. 이는 원자로에서의 노심용융사고 발생시 그 결과를 완화시키는 한 방법으로 고려되고 있는 원자로용기 외부 냉각 (Ex-Vessel Flooding) 개념과 연관된다. 대기압하, 포화상태 물에서 너비가 다른 두 개의 평판 (20mm×200mm 및 25mm×200mm)을 이용, -90°(평형 하향), -88°, -86°, -84°, -60°와 -40°의 경사 각도에 대한 임계열유속이 측정되었다. 실험 결과 너비가 큰 평판에서, 그리고 수직 위치로부터의 각도가 클수록 임계열유속이 낮게 나타났다. 이는 가열면에서 발생된 기포들의 이탈이 어려워지기 때문인 것으로 판단된다. 경사 각도에 따른 전체적인 임계열유속 경향은 기존 연구들과 대체로 일치하나, 임계열유속 감소율이 변화하는 천이 각도가 -80° 근방에서 발견되었다.

1. Introduction

Ex-vessel flooding, flooding of the reactor cavity of a pressurized water reactor (PWR) or the drywell(or supression pool) of a boiling water reactor (BWR), is being investigated as a mitigating measure of a severe accident which results from a hypothetical loss-of-coolant accident (LOCA) coupled with the failure of the emergency core cooling system (ECCS) [1]. The main objective of ex-vessel flooding is to maintain the integrity of reactor vessel bottom head containing the molten core material indefinitely by cooling the outside surface of the vessel. At low heat flux, the heat would be removed by single-phase natural convection. As heat flux increases, pool boiling occurs at the outside surface of the reactor vessel, showing different heat transfer modes depending on the heat flux and cooling water conditions.Therefore, it is important to investigate the heat transfer characteristics as a function of angular position on the outside surface of the reactor vessel bottom head. In particular, the CHF is important to assess the maximum possible heat transfer rate which determines the feasibility of ex-vessel flooding.

The pool-boiling CHF is the CHF occurring on a heated surface submerged in a large amount of stagnant liquid.There have been many experiments with discs, cylinders, upward-facing plates or vertical plates, but only a few with inclined plates or downward-facing plates. The CHF condition on a horizontal upward-facing surface is explained well by Zuber's model based on the hydrodynamic instability near the heated surface [5]. CHF mechanisms on downward-facing surfaces, either horizontal or inclined, can be significantly different, because of the difference in bubble behavior.

A series of CHF experiments on downward-facing plates are being performed in KAIST, with varying the size and orientation of the plates and cooling water conditions. This paper presents the results of the first-phase experiments performed with two test sections of different width.

2. Previous Work

A limited number of experiments have been reported on the pool-boiling heat transfer characteristics for downward-facing plates, as summarized in Table 1. In Table 1, the inclination angle is defined as the angle measured from the vertical position, in such a manner that it becomes 90°, 0°, and -90° for the horizontal upward-facing, vertical, and horizontal downward-facing plates, respectively.

Githinji and Sabersky [6] studied the boiling curve for 3 different surface orientations (facing up, vertical, and facing down), using a 3-mm-width strip in a pool of 80oF isopropyl alcohol under atmospheric pressure. They showed that the boiling curve for the horizontal downward-facing surface was different from those for other orientations.The CHF for the downward surface was considerably lower than that for other orientations. Vishnev et al. [7] performed experiments and presented a CHF correlation for he-

Table 1. Experimental Ranges

Author	Pool property	Angle range (°)	Heater size (cm)	Remarks
Githinji & Sabersky [6]	Isopropyl alcohol	−90, 0, 90	0.3175×10.16	CHF & Boiling curve
Vishnev et al. [7]	Helium	−90 − 90	1.04×9.6	CHF
Jung et al. [10]	Freon	−90 − 90	Φ 7.8	Boiling curve in nucleate boiling
Guo & El-genk [8]	Water	−90 − 0	Φ 5. 08	Pool boiling curve
Nishikawa et al. [9]	Water	−85 − 90	17.5×4.2	Heat transfer in the nucleate boiling
Present	Water	−90 − −60	2/2,5×20	CHF

In the angle region column, 0 means vertical.

lium boiling on a plate, varying the inclination angle. They found that the CHF decreased as the heated surface orientation was changed from upward to downward. Guo and El-Genk [8] obtained pool-boiling curves for water on downward-facing and inclined surfaces, by quenching a 12.8-mm-thick copper disk of 50.8-mm-diameter. The effect of the inclination angle on the heat transfer coefficient depended on the boiling regime:

a) nucleate boiling heat transfer increased with the decrease in the inclination angle (from 0° to -90°), although this effect was decreased with the wall superheat and even reversed near the CHF; and

b) all the CHF, the transition boiling heat transfer, the minimum heat flux, and the film boiling heat transfer decreased with the decrease in the inclination angle and showed the minimum at the downward-facing case.

There have been some experimental studies on other pool boiling phenomena for downward-facing plates. Nishikawa et al. [9] performed experiments for nucleate pool boiling of water, with varying the inclination angle of a rectangular plate (42mm × 175mm) from 90° to -85°. Their experimental results showed that the surface orientation effect was remarkable at low heat fluxes and the heat transfer coefficient became large as the inclination angle was decreased, while no marked effect was observed at high fluxes. No data were reported for the horizontal downward-facing or the CHF. Jung et al. [10] investigated the surface orientation effect on both nucleate and film boiling of R-11, using a 78-mm-diameter disc heater. The effect on nucleate boiling was not clear at surface heat fluxes above 40kW/m^2 for variation of the inclination angle from +90° to -75°. They identified two nucleate boiling mechanisms: (a) the evaporative mechanism that always existed and was independent of the surface orientation, and (b) the bubble agitation mechanism that heavily depended on the orientation of the heated surface.

3. Experiments

3.1. Experimental Apparatus

The schematic diagram of the experimental loop is shown in Fig. 1. The loop, which operates under atmospheric pressure, consists of a test section, a test pool, a pre-heater, an overhead tank, a centrifugal pump, a temperature controller, valves, and connecting pipes. Most parts of the loop are made of Type-304 stainless steel to minimize corrosion and to allow easy cleaning.

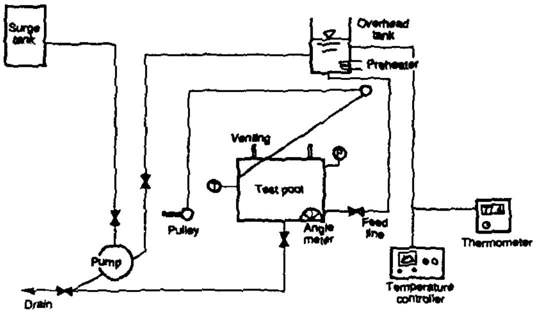
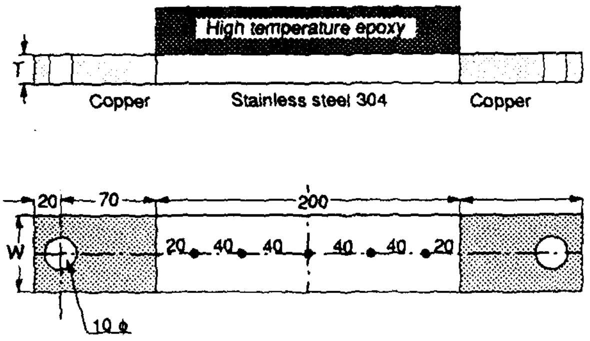


Fig. 1. Schematic Diagram of Experimental Loop



	Width	Length	Thickness
Test section 1	20	200	0.5
Test section 2	25	200	0.5

(unit: mm)

Fig. 2. Schematic Diagram of Test Sections

Two test sections have been used, as shown in Fig. 2. Direct joule heating of the Type 304 stainless steel plate was applied to provide uniform heat flux. The upper surface of the test section was insulated by high-temperature-resistant epoxy, to minimize heat loss. The temperature of the stainless steel plate was measured by five (5) Chromel-Alumel (Type-K) thermocouples embedded at the boundary between the heated plate and the insulating epoxy. A copper electrode was welded to each end of the stainless steel plate to transfer electric power from a 100V, 700A DC power supply system. The test sections were located near the center of the test pool to minimize the effect of pool geometry.

The test pool, as shown in Fig. 3, was made of Type-304 stainless steel except for the front and back parts that were made of glass to allow visual observation. Three Copper-Constantan (Type T) thermocouples were used to measure the temperature of the pool water. The overhead tank was used to control the test-pool water level maintaining the test pool pressure near atmospheric. The 3kW preheater was used to preheat the pool water to a desired temperature using the temperature controller. A pulley was installed at the side of the experimental loop, to control the orientation of the test section. To get an inclination angle, the test pool was rotated as a whole, instead of rotating the test section.

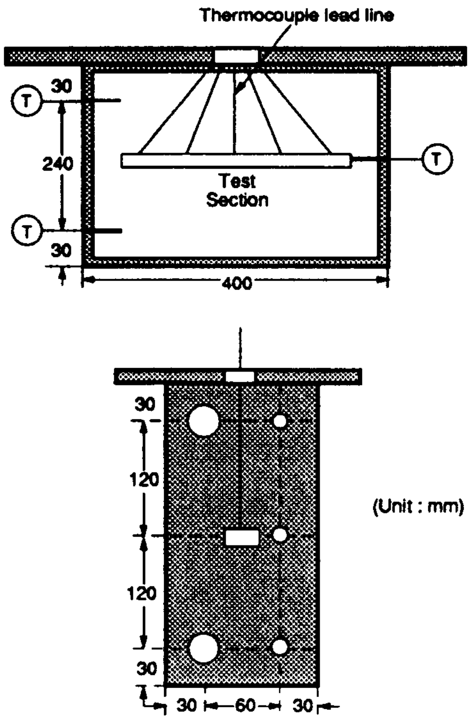


Fig. 3. Schematic Diagram of Test Pool

The power to the test section, i.e. the voltage, and the temperatures of the heated plate and the 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/386. 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°. The error in the heat flux measurement was estimated to be around 4%.

3.2. Experimental Procedure

Each measurement of the CHF was conducted according to the following procedure:

1. Polish and clean the heater surface prior to each test.
2. Fill the test loop with filtered water, circulate the water along the loop with heating to reduce the noncondensable gas content in the loop water.
3. Achieve a desired pool temperature using the preheater and the temperature controller.
4. Fix the test section orientation at desired angle using the angle meter.
5. Start the data acquisition system.
6. Power on the DC power supply system.
7. Increase the power input step by step until the CHF condition is reached.
8. On occurrence of the CHF, immediately trip the test section power.
9. After recording important results, return to step 1 or 4 according to the heater surface condition, or

stop the test.

During the experiment, every effort was made to maintain the clean heating surface condition for all runs. A selected number of repeated tests were performed for the same test condition to assess the reproducibility of the CHF data.

The CHF condition was defined as the condition that maximum wall temperature increased continuously and exceeded 200°C. This was because preliminary experiments indicated that the wall temperature increased abruptly to above 400°C once it exceeded about 200°C.

3.3. Test Range

The test range of the present work is summarized in Table 2. Measurements were made for various inclination angles: -90°, -88°, -86°, -84°, -60° and -40°. Further experiments for the inclination angle above -40° were impossible due to the problem of venting and/or due to the limitation of the power supply system. The pool water was maintained at saturated condition under near atmospheric (~112kPa) throughout the experiments.

Table 2. Experimental Matrix of Present Works

	-40°	-60°	-84°	-86°	-88°	-90°
T/S-1	P1-40	P1-60	P1--84	P1-86	P1-88	P1-90
T/S-2	-(*)	P2-60	P2-84	P2-86	P2-88	P2-90

* Test was impossible due to the limitation of the power supply.

4. Results and Discussion

4.1. Overall Behavior and Parametric Trends

Table 3. Experimental Results of Test Section 1

Degree (°)	Voltage (V)	Ampere (A)	Critical Heat Flux (kW/m²)	RMS (%)
−90	6.95	450	782	2.32
	6.95	451	784	
	6.84	445	761	
−88	7.39	479	885	2.36
	7.31	470	856	
−86	7.40	484	895	2.78
	7.53	495	931	
−84	7.78	511	994	2.91
	7.83	513	1004	
	7.69	504	965	
−60	7.83	515	1008	0.28
	7.85	516	1012	
−40	8.26	538	1111	3.52
	8.05	525	1057	

Table 4. Experimental Results of Test Section 2

Degree (°)	Voltage (V)	Ampere (A)	Critical Heat Flux (kW/m²)	RMS (%)
−90	5.83	441	514.2	5.47
	5.62	430	483.3	
	5.84	441	515.1	
−88	6.36	485	616.9	1.18
	6.44	487	627.3	
−86	6.69	507	678.4	4.04
	6.92	519	718.3	
−84	7.42	555	826.7	6.16
	7.44	557	828.8	
−60	7.83	587	919.2	2.77
	8.02	596	956.0	

Table 3 and 4 summarize the measured CHF data. The data are also shown in Fig. 4, compared with experimental data by Guo and El-Genk [8] and predictions for an upward-facing plate of an infinite size [5, 11]. Important observations were:

a) The CHF decreased with the decrease in the inclination angle. Two ranges were identified according to the rate of change: (a) the gradual change region for the inclination angle above a transition angle, and (a) the steep change region for the inclination angle below the transition angle. The transition angle appeared to be around -80°.
b) Lower CHFs were measured for the test section of

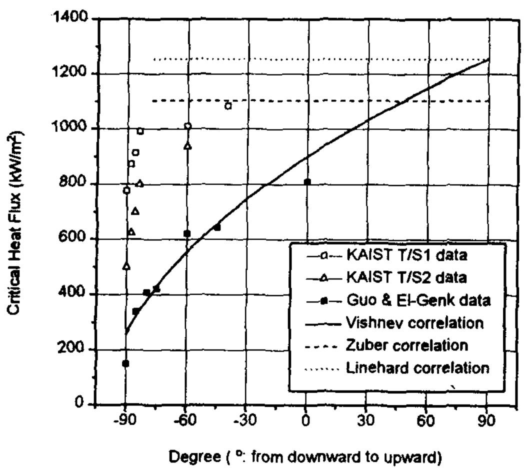


Fig. 4. Overall CHF Behavior

the larger width. This can be attributable to the increased difficulty of bubble escape for the wider test section.

c) The CHF data of Guo and El-Genk were much lower than the present data. This would be due to the disc diameter (50.8mm) that is considerably larger than the widths of the present test sections (20mm and 25mm).

d) The measured CHFs were, as expected, much lower than those predicted by the following conventional pool-boiling CHF correlations for an infinite upward flat plate:

$$q_c = K\rho_g^{1/2} h_{fg} \sqrt[4]{g\sigma(\rho_f-\rho)_g} \qquad (1)$$

where K = 0.149 by Lienhard & Dhir [11], 131 by Zuber [5]
ρ^g = vapor density
ρ^f = liquid density
h^{fg} = latent heat of vaporization
g = gravitational acceleration
σ = surface tension

4.2. Visual Observations

The observed behavior of bubbles near the heated surface is represented in Fig. 5. The behavior varied according to the inclination angle.

Horizontal Downward Facing

At low heat fluxes, small bubbles were generated and stayed at a limited number of nucleation sites. With the increase in heat flux, bubbles gradually grew and coalesced with surrounding bubbles into larger ones. As they grew to sufficiently large ones, they escaped from the heated surface mainly through lateral sides. At high heat fluxes, bubbles were vigorously generated over the heated surface and large bubbles escaped from the heated surface through all sides. The CHF occurred at an arbitrary point.

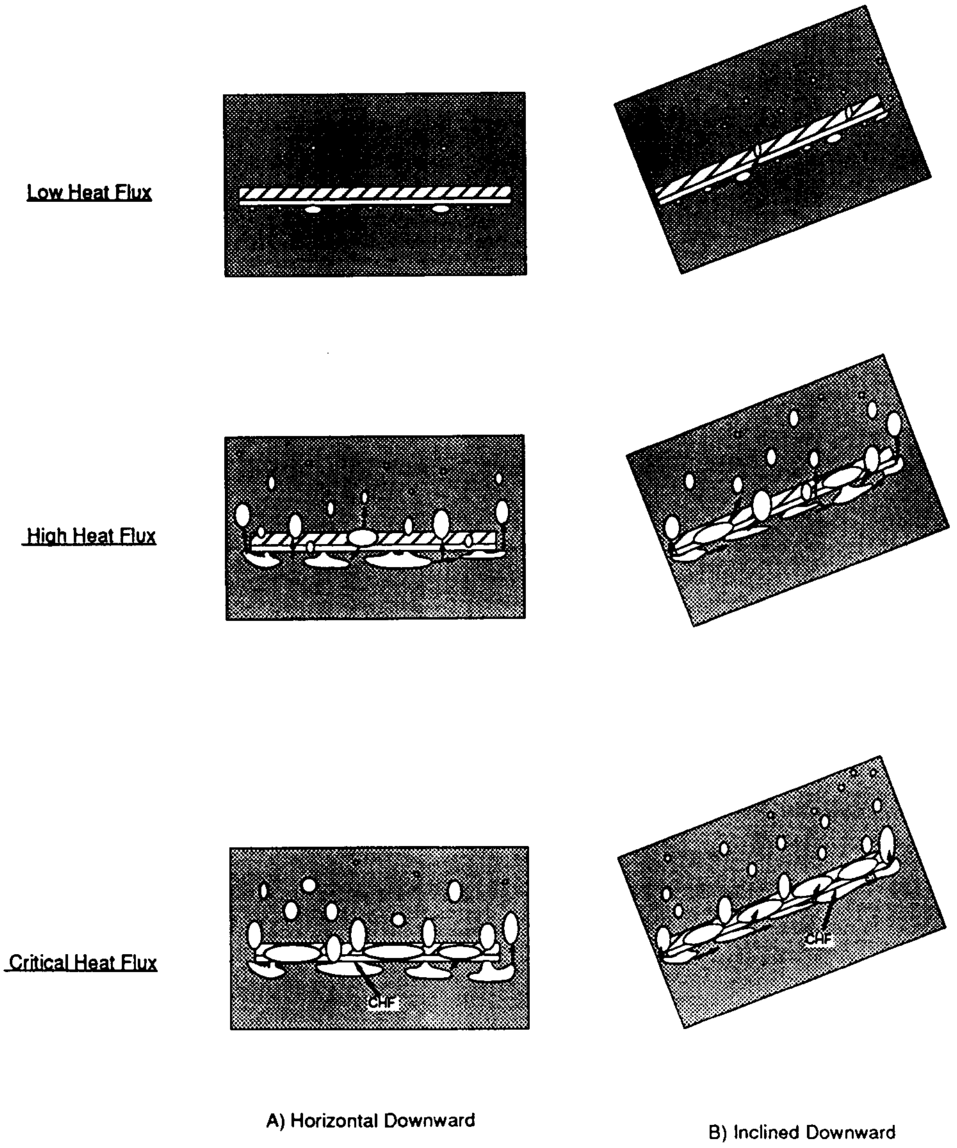
Inclined Downward Facing

For inclined downward-facing plates, small bubbles generated at nucleation sites slid along the heated surface and escaped through the upper edge of the plate due to buoyancy force even at low heat fluxes. The bubble behavior became similar to that for the horizontal downward facing at high heat fluxes, except for the sliding effect. The CHF generally occurred on the lower part of the heated surface.

4.3. Further Discussion

Overall, the experimental results are consistent with those by previous workers from the viewpoint of the effects of the heater size and the inclination angle.

Experimental data showed the importance of the heater size on the CHF. As discussed earlier, it can be related to the mechanism of bubble escape from the heated surface: it is more difficult for bubbles to escape on the larger plate. In this regard, the width of a rectangular plate or the diameter of a plane disk can be considered as the characteristic size. It is thought that there exists a threshold characteristic size, as a function of fluid properties and the heater



A) Horizontal Downward

B) Inclined Downward

Fig. 5. Boiling Mechanism of the Inclined Heated Surface

shape, above which the size effect becomes insignificant. To find the threshold size, some more tests would be required with increasing the width of the test section. The CHF on the reactor vessel outside surface can be reasonably investigated, using a plate test section of the size larger than the threshold value.

The bubble behavior postulated in Fig. 5 should be investigated further. However, it can be said that boiling on an inclined downward-facing plate is a mixing of two different boiling mechanisms: (a) the boiling on a vertical plate, and (b) the boiling on the horizontal plate. For the inclination angle above a certain transition angle (~ -80°), the decrease in the CHF was small due to sufficient sliding of bubbles along the heated surface. When the inclination angle further decreased from the transition angle, the sliding of bubbles became much more difficult, resulting in the lower CHF.

A selected number of repeated tests were conducted for the same condition to check the reproducibility of the experimental data. The last columns of Tables 3 and 4 show relatively good reproducibility for both test sections.

Finally, Figures 6 and 7 show the traces of surface heat flux against the surface temperature.

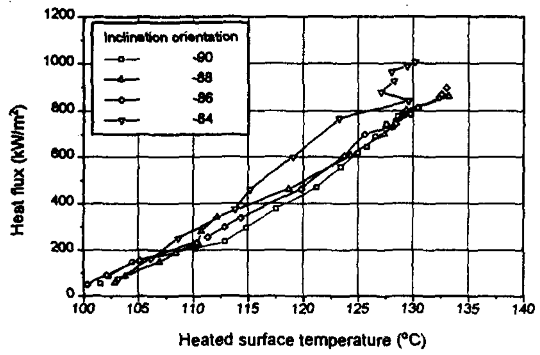


Fig. 6. Temperature-Heat Flux in Test Section 1

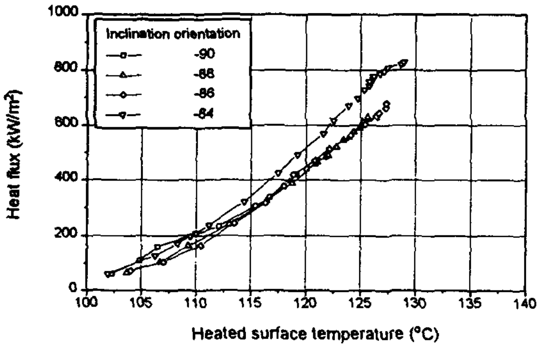


Fig. 7. Temperature-Heat Flux in Test Section 2

5. Conclusions and Recommendations

Two plate-type test sections with different widths were used to investigate the CHF on downward-facing plates. The important results of present study are as follows:

a) The CHF decreased with the decrease in the inclination angle. The existence of a transition angle was identified based on the CHF decrease rate with the angle.

b) The lower CHFs were measured for the test section with the larger width. This can be attributable to the increased difficulty of bubble escape for the wider test section.

c) Test results were generally consistent with those by previous workers.

d) Figure 5 provides a basis for detailed investigation on the boiling mechanism.

Further work would be required on the following aspects:

a) effects of the heater size including the identification of the threshold size,

b) effects of the inclination angle including the confirmation of the transition angle,

c) effects of the system operating parameters, e.g., subcooling and pressure of the pool water, and

d) clear identification of governing mechanisms including mathematical modeling.

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