# Pool Boiling CHF in Inclined Narrow Annuli

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## 1. Introduction

Pool boiling heat transfer has been studied extensively since it is frequently encountered in various heat transfer equipments. Recently, it has been widely investigated in nuclear power plants for application to the advanced light water reactors designs. Through the review on the published results it can be concluded that knowledge on the combined effects of the surface orientation and a confined space on pool boiling heat transfer is of great practical importance and also of great academic interest [1].

Fujita et al. [1] investigated pool boiling heat transfer, from boiling inception to the critical heat flux (CHF, $q''_{CHF}$), in a confined narrow space between heated and unheated parallel rectangular plates. They identified that both the confined space and the surface orientation changed heat transfer much. Kim and Suh [2] changed the surface orientation angles of a downward heating rectangular channel having a narrow gap from the downward-facing position (180º) to the vertical position (90º). They observed that the CHF generally decreased as the inclination angle ($\theta$) increased.

Yao and Chang [3] studied pool boiling heat transfer in a confined heat transfer for vertical narrow annuli with closed bottoms. They observed that when the gap size ($s$) of the annulus was decreased the effect of space confinement to boiling heat transfer increased. The CHF was occurred at much lower value for the confined space comparing to the unconfined pool boiling. Pool boiling heat transfer in narrow horizontal annular crevices was studied by Hung and Yao [4]. They concluded that the CHF decreased with decreasing gap size of the annuli and described the importance of the thin film evaporation to explain the lower CHF of narrow crevices.

The effect of the inclination angle on the CHF on countercurrent boiling in an inclined uniformly heated tube with closed bottoms was also studied by Liu et al. [5]. They concluded that the CHF reduced with the inclination angle decrease.

A study was carried out by Kang [6] to identify the combined effects of the surface orientation and a confined space on pool boiling heat transfer in annuli. The gap size was 15 mm and the annuli with both open and closed bottoms were considered. At a given heat flux, the heat transfer coefficient was increased with the inclination angle increase. However, no occurrence of the CHF was observed regardless of the flow inlet condition for the given gap size and heat fluxes tested.

Summarizing the published results, it can be said that the narrow gap size, restriction of the bottom inlet flow into the confined space, and the inclination angle not only changes nucleate boiling heat transfer but also initiates the CHF. Therefore, the present study is aimed at the investigation of the effects of a narrow gap size (5 mm) on pool boiling heat transfer in inclined annuli to improve Kang's previous results [6].

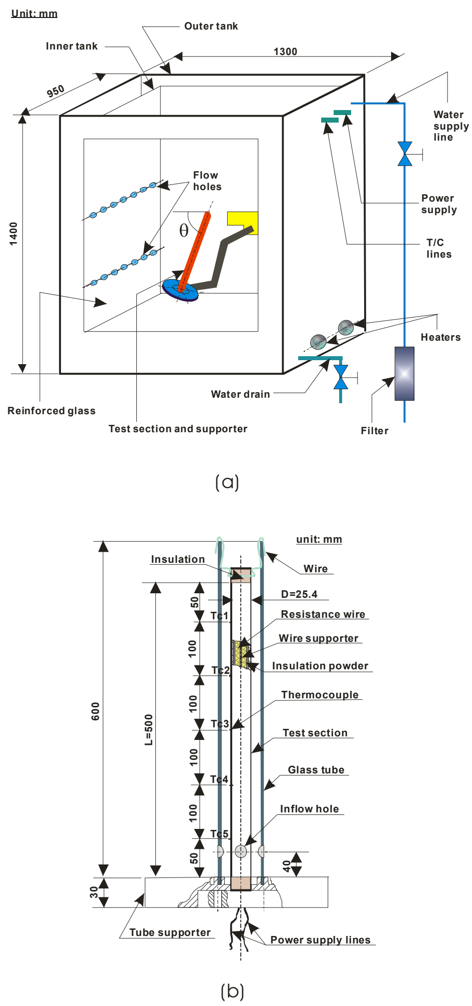


Fig. 1. Schematics of the experimental apparatus.

## 2. Experiments and Results

A schematic view of the present experimental apparatus and an assembled test section is shown in Fig. 1. The sizes of the inner tank were 800×1000×1100 mm (depth×width×height). The heat exchanging tube was simulated by a resistance heater (Fig. 1b) made of a very smooth stainless steel tube. Electric power of 220 V AC was supplied through the bottom side of the tube.

The tube outside was instrumented with five T-type sheathed thermocouples. A glass tube of 35.4 mm inner diameter and 600 mm length was used to make an annulus. The inclination angle is measured from the horizontal position as depicted in Fig. 1a. The heat flux from the electrically heated tube surface was calculated from the measured values of the input power and the effective heated area.

The uncertainties of the experimental data were calculated from the law of error propagation [7]. The 95 percent confidence uncertainty of the measured temperature had the value of ±0.11 °C. The uncertainty in the heat flux was estimated to be ± 0.7% and the uncertainty of the heat transfer coefficient was determined to be ± 6%.

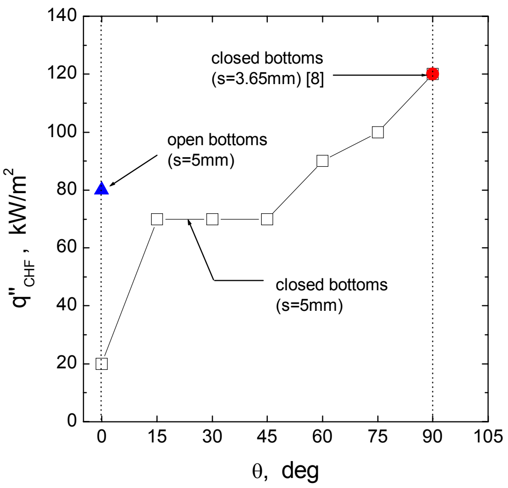


Fig. 2. Changes in the CHF with the inclination angle.

In the annulus of the narrow gap size the occurrence of the CHF is observed at relatively small heat fluxes as shown in Fig. 2. The occurrence of the CHF is defined when the wall temperature at the measuring location increases continuously in an excursion. The location of the CHF occurrence for the annulus with closed bottoms is nearby the outlet of the annulus (i.e., T/C1 point). At 90º (i.e., vertical position), the value of the CHF is 120 kW/m². The value is same to the CHF for the vertical annulus of 3.65 mm gap with closed bottoms [8]. This denotes that the CHF in the vertical annulus with closed bottoms has the same value when the gap size ranges from 3.65 mm to 5 mm. As the inclination angle decreases to the horizontal position (i.e. 0º), the CHF decreases gradually to 20 kW/m². When the inclination angle is ranging from 45º to 15º the CHF for the angles is same and has the value of $q''_{CHF}$ =70 kW/m². A sudden decrease in the CHF was observed as the inclination angle varies from 15º to 0º. For the present annulus $q''_{CHF}$ =20 kW/m² at $\theta$=0º. This value is much smaller than the CHF for the annulus of $s$ =5 mm with open bottoms. The CHF for the annulus with open bottoms is 80 kW/m². Since there are two side outlets for the annulus with open bottoms, bubbles get out of the confined space more easily than the annulus with closed bottoms, and this delays the creation of bigger coalesced bubbles in the space. Moreover, the location of the CHF is different from each other. The location is nearby the outlet for the annulus with closed bottoms whereas it is the mid-length of the annulus with open bottoms.

Reviewing the published results of confined space of different geometries it is identified that the initiation of CHF depends on the creation of big size bubbles on the heated surface through coalescence with other bubbles resulted from the insufficient liquid supply to the confined space. In other words, the major mechanism affecting on the CHF is dryout of the liquid film under the deformed coalesced bubbles. When the surface inclination angle decreases to the horizontal position the bubbles gradually lose buoyancy and coalesce together more easily than the vertical position. As the size of the coalesced bubble gets increased the liquid on the outside of the crevice can hardly get into the crevice. And, thereafter, the liquid film under the coalesced bubbles dried out in a short time period.

## 3. Conclusions

An experimental study was carried out to investigate the combined effects of the heated surface orientation and flow confinement on pool boiling CHF of saturated water at atmospheric pressure. The gap size was 5 mm and annuli with both open and closed bottoms were considered. The CHF reduced from 120 to 20 kW/m² as the orientation of the annuli changes from the vertical to the horizontal positions.

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