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Critical heat flux of countercurrent boiling in an inclined small tube with closed bottom☆

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ABSTRACT

The study was focused on the effect of the inclination angle on the critical heat flux of countercurrent boiling in an inclined uniformly heated tube with open top and closed bottom ends at zero inlet flow. The experimental results show that the CHF data of the small vertical tubes agree reasonably well with the predicting correlation proposed by Tien. The CHF data of the small inclined tubes decrease with reducing the inclination angle. The experimental data of the inclined tubes agrees reasonably well with the modified correlation, which is resulted from the conventional correlation for vertical tubes.

1. Introduction

Two-phase thermosyphon, which utilizes gravitation and phase change of liquid contained in a vertical or inclined tube for heat transfer without the aid of external work, has been researched extensively for many years for different geometric configurations in order to investigate the heat transfer characteristics and the operating limits. The understanding of the critical heat flux due to flooding in the thermosyphon is a necessary and important work in the heat transfer field.

The CHF of countercurrent boiling in a vertical tube or rectangular channel at zero inlet flow is considered as a phenomenon closely related to flooding which is a limiting condition in countercurrent flow. Therefore, the most generalized correlations for the CHF data of countercurrent boiling depend mainly on flooding. A large amount of studies have been carried out, and various correlations have been reported in the literature for predicting the CHF in a vertical tube or rectangular channel with closed bottom [1–11]. The general form of these correlations may be expressed as,

$$Ku = f\left(\frac{D}{L}\frac{\rho_g}{\rho_l}Bo\right). \tag{1}$$

Tien [2] proposed a semi-theoretical predicting correlation for the CHF of vertical channels as follows,

$$Ku = \frac{D}{4L}\frac{3.2}{\left[1+\left(\rho_g/\rho_l\right)^{1/4}\right]^2}. \tag{2}$$

When $Bo \geq 30$, Tien and Chung [3] proposed a modified correlation to consider the effect of Bond number,

$$Ku = \frac{D}{4L}\frac{3.2\tanh\left(0.5Bo^{1/4}\right)}{\left[1+\left(\rho_g/\rho_l\right)^{1/4}\right]^2}. \tag{3}$$

Katto and Hirao [5] presented an empirical correlation for predicting the CHF in a vertical tube,

$$Ku = \frac{0.10}{1+0.491(L/D)Bo^{-0.3}}. \tag{4}$$

Nejat [6] carried out a systemic experiment and proposed an empirical correlation for a vertical tube,

$$Ku = \frac{D}{4L}\frac{0.36Bo^{1/2}}{\left[1+\left(\rho_g/\rho_l\right)^{1/4}\right]^2}\left(\frac{L}{D}\right)^{0.1}. \tag{5}$$

Imura and co-workers [7] presented a following correlation by a regular tube experiment,

$$Ku = 0.16\frac{D}{L}\left(\frac{\rho_l}{\rho_v}\right)^{0.13}. \tag{6}$$

Smirnov [8] presented a following correlation for vertical rectangular channels,

$$Ku = 0.64\frac{D}{4L}\left(\frac{\rho_l}{\rho_g}\right)^{0.1}. \tag{7}$$

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Nomenclature

Bo	Bond number, $Bo = \frac{D}{(\sigma/g(\rho_l - \rho_v))^{1/2}}$
C_w	empirical constant
D	inner diameter of the test tube (m)
g	constant of gravitation acceleration (m/s^2)
h_{fg}	latent heat of evaporation (J/kg)
Ku	Kutateladze number, $Ku = \frac{q_c/h_{fg}\rho_v}{(\sigma g(\rho_l - \rho_v)/\rho_v^2)^{1/4}}$
L	heated length of the test tube (m)
q	heat flux (W/m^2)
q_c	critical heat flux (W/m^2)
T	wall temperature (K)
t	time (s)
ΔT_{sat}	superheat (K)

Greek letters

σ	liquid–gas interface tension (N/m)
ρ	density (kg/m^3)
θ	inclination angle

Subscripts

l	liquid phase
g	gas phase

Monde et al [9,10] proposed a semi-theoretical correlation for a vertical tube,

$$Ku = 0.1031 Bo^{1/8} \frac{D}{L} \left(\frac{\rho_l}{\rho_g}\right)^{1/7}. \quad (8)$$

Park and co-workers [11] compared various existing predicting correlations and obtained a more accurate correlation as follows,

$$Ku = \frac{D}{4L} \frac{C_w Bo^{1/2}}{\left[1 + \left(\rho_g/\rho_l\right)^{1/4}\right]^2} \quad (9)$$

where

$$C_w = 1.22\left(\frac{L}{D}\right)^{0.12}\left(\frac{\rho_g}{\rho_l}\right)^{0.064}\left(1 + 0.055Bo - 4.08 \times 10^{-3} Bo^2\right).$$

Compared with the CHF for vertical tubes with closed bottom, although the inclined tubes are also frequently used in actual engineering applications, the study concerning the boiling characteristics and the CHF in the inclined tubes with closed bottom has not been reported.

In the present study, as shown in Fig. 1, an experimental study of countercurrent boiling was carried out to investigate boiling phenomena and the CHF in a uniformly heated, inclined tube with closed bottom, which was submerged in a pool of saturated liquid. The purpose of the study is to discover the effect of inclination angle on the CHF in a small inclined tube at zero inlet flow. Both saturated liquids of water and R-113 were used as working liquids. The inner diameters of the tested tubes ranged from 2.1 mm to 4.0 mm. The tube lengths changed from 100 mm to 300 mm and the inclination angles varied from 90° to 0°. The experimental results show that the CHF decreases with increasing the ratio of the tube length to the tube diameter and decreasing the inclination angle. A conventional CHF predicting correlation which used on vertical tubes was modified by considering the effect of the gravitation caused by the inclination angle on the falling liquid film. The modified correlation can reasonably well predict the CHF for the inclined tube.

2. Experimental apparatus and procedure

Fig. 2 shows the schematic diagram of the experimental apparatus. The test tube was a round tube made of thin stainless steel and was directly linked with direct current supplied by a silicon rectifier to produce joule heat. The output power was measured with a standard resistor unit to promote the measurement precision. The wall heat flux was calculated from the output electric power and the effective heated area. There was a quite thick silica insulating layer outside the tube. Seven thermocouples were welded at the outside of the tube as shown in Fig. 3 to measure the wall temperatures at axial and circumferential directions respectively. All thermocouples were linked with a temperature controller and a multi-channel digital voltmeter that measured the wall temperature variations. The test tube was fixed in a round test vessel made of stainless steel whose length and outer diameter were 1.0 m and 0.1 m. The test vessel was fixed on a soleplate and its inclination angle could be adjusted by using the hinges and supporting brackets.

The CHF was estimated theoretically prior to each test. When the test began, the output electric power was set to 60% of the estimated CHF. After the temperature reached the steady state, the power was then increased in an increment of 5% of the estimated CHF. When the measured wall temperatures firstly increased abruptly and could not attain a steady state, which indicated that a dry-out phenomenon occurred on the wall, the electric power supply was instantly switched off. Then, the run was restarted from the former steady output power and the power was then increased in an increment of 1% of the estimated CHF. When the measured wall temperatures increased abruptly and could not attain a steady state again, the electric power supply was instantly switched off and the test was stopped. The CHF value was determined from the output electric power of the former time. Distilled water and R113 were used as the test fluids and the tests were under atmospheric pressure. The effective heated lengths of the test tubes were 100 mm, 200 mm and 300 mm respectively. The inner diameters of the test tubes were 2.1 mm, 3.0 mm and 4.0 mm. L/D ranged from 25 to 143. The inclination angles varied from vertical position to horizontal position in an increment of 15°. The measurement error of heat flux caused by the instruments was less than 1%. That caused by the effective heated area was less than 0.5%. That caused by the heat losses was less than 1% and that caused by the interceptive measurement error by increment in the output power was less than 1%. The maximum uncertainty of the CHF was within ±3.5%.

3. Experimental results and discussion

3.1. Derivation of the modified correlations for the inclined small tubes

Monde [9,10] proposed a maximum falling liquid concept for predicting theoretically the CHF of countercurrent boiling in a vertical

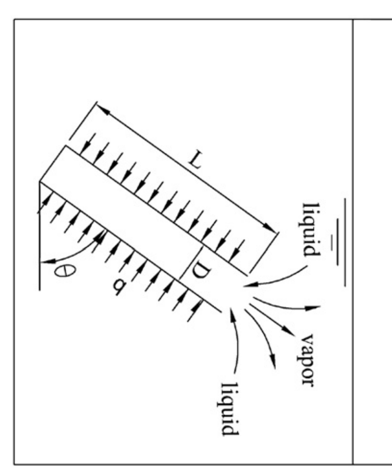

Fig. 1. Flow configurations of liquid and vapor in an inclined tube with closed bottom end.