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Pool boiling heat transfer on a vertical tube with a partial annulus of closed bottoms

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Abstract

To improve pool boiling heat transfer in an annulus with closed bottoms, the length of an outer tube has been changed between 0.2 m and 0.6 m. A heated tube of 19.1 mm diameter and the water at atmospheric pressure have been used. Three annular gap sizes of 3.65, 6.35, and 17.95 mm have been investigated. To elucidate effects of the outer tube results of the annulus are compared with the data of a single unrestricted tube. The change in the outer tube length results in much variation in heat transfer. As the outer tube length is much shorter than the heated tube the deterioration point of heat transfer gets moved up to the higher heat fluxes and the possibility of CHF creation is prevented. The major cause of the tendencies is related with the decrease in the intensity of bubble coalescence.

Keywords: Pool boiling; Annulus; Closed bottoms; Vertical tube

1. Introduction

The mechanism of pool boiling heat transfer has been studied extensively in the past since it is closely related with the thermal design of more efficient heat exchangers [1,2]. To have higher heat transfer coefficients is very important if the space for heat exchanger installation is very limited like advanced light water reactors [2,3]. One of the effective means to increase heat transfer is to consider a confined geometry. Major geometries concerning about the crevices are annuli [4–8] and plates [9,10]. Some geometry has closed bottoms [4,6–9]. Some previous studies about the annuli are listed in Table 1.

It is well known from the literature that the confined boiling can result in heat transfer improvement up to 300–800% at low heat fluxes, as compared with unconfined boiling. However, a deterioration of heat transfer appears at higher heat fluxes for confined than for unrestricted boiling [4,6,7]. According to Kang [6], once the flow inlet at the tube bottom is closed, a very rapid increase in the heat transfer coefficient (h_b) is observed at low wall superheat (ΔT_{sat}) less than 2 K. However, increasing ΔT_{sat} more than 2 K the coefficient has almost the same value (i.e. about 20 kW/m^2 K) regardless of the heat flux increase. The cause for the deterioration was suggested as bubble coalescence at the upper regions of the annulus [4]. To adopt the vertical annulus with closed bottoms for the thermal design of a heat exchanger more detailed studies to prevent the deterioration is needed.

Up to the author's knowledge, no previous results concerning the ways have been published yet except the author's preliminary study [8]. Recently, Kang [8] published some results of the vertical annulus (6.35 mm gap) with closed bottoms. To remove the coalescence of the big size bubbles around the upper region of the annulus Kang [8] controlled the length of the outer tube (L_o) of the annulus. The change of the outer length results in much variation in heat transfer coefficients. As the length of the outer tube is much shorter than the length of the heated tube (L) the deterioration point of heat transfer gets moved up to the higher heat fluxes. The reduction of the gap size

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Nomenclature

C	parametric constant	q''	heat flux
D	heating tube diameter	s	annular gap size
h_b	boiling heat transfer coefficient	T_{sat}	saturation temperature
I	supplied current	T_W	tube wall temperature
L	heated tube length	t	time
L_o	outer tube length	V	supplied voltage
L_R	ratio of the tubes ($=L_o/L$)	ΔT_{sat}	tube wall superheating ($=T_W - T_{sat}$)

Table 1
Summary of previous works about annular gap effects on pool boiling heat transfer

Author	Remarks
Yao and Chang [4]	– heater: stainless steel tube ($D = 25.4$ mm, $L = 25.4$ and 76.2 mm) – liquid: R-113, acetone, and water at 1 atm – liquid condition: saturated – geometry: vertical annuli with closed bottoms – gap sizes: 0.32, 0.80, and 2.58 mm
Hung and Yao [5]	– heater: stainless steel tube ($D = 25.4$ mm, $L = 101.6$ mm) – liquid: R-113, acetone, and water at 1 atm liquid condition: subcooled or saturated – geometry: horizontal annuli – gap sizes: 0.32, 0.80, and 2.58 mm
Kang [6]	– heater: stainless steel tube ($D = 25.4$ mm, $L = 570$ mm) – liquid: water at 1 atm – liquid condition: saturated – geometry: vertical annuli with open or closed bottoms – gap sizes: 3.9 and 15 mm
Kang and Han [7]	– heater: stainless steel tube ($D = 25.4$ mm, $L = 500$ mm) – liquid: water at 1 atm – liquid condition: saturated – geometry: vertical annuli with open or closed bottoms – gap sizes: 3.9, 15.0, 25.1, 34.9, and 44.3 mm
Kang [8]	– heater: stainless steel tube ($D = 19.1$ mm, $L = 540$ mm) – $L_o = 200$, 400, and 600 mm – liquid: water at 1 atm – liquid condition: saturated – geometry: vertical annuli with closed bottoms – gap sizes: 6.35 mm

(s) also enhances heat transfer [7]. To clarify effects of the outer tube on heat transfer other gap sizes should be studied since the difference in the gap size could results in different tendencies. The present study is to analysis heat transfer in the annulus with closed bottoms through changing the length of the outer tube and the gap size of the annulus.

2. Experiments

A schematic view of the present experimental apparatus and a test section is shown in Fig. 1. The water storage tank (Fig. 1(a)) is made of stainless steel and has a rectangular cross section (950 × 1300 mm) and a height of 1400 mm. The sizes of the inner tank are 800 × 1000 × 1100 mm (depth × width × height). The inside tank has several flow holes (28 mm in diameter) to allow fluid inflow from the outer tank. Four auxiliary heaters (5 kW/heater) were installed at the space between the inside and the outside tank bottoms. The heat exchanger tubes are simulated by a resistance heater (Fig. 1(b)) made of a very smooth stainless steel tube ($L = 0.54$ m and $D = 19.1$ mm). The surface of the tube was finished through buffing process to have smooth surface. 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 (diameter is 1.5 mm). The thermocouple tip (about 10 mm) was bent at a 90° angle and was brazed on the tube wall. The water temperatures were measured with six sheathed T-type thermocouples brazed on a stainless steel tube that placed vertically at a corner of the inside tank. Since the fluid flow is very turbulent the physical mechanism and the temperature reading is not much disturbed by the brazing points. Therefore its effect is neglected. All thermocouples were calibrated at a saturation value (100 °C since all tests were done at atmospheric pressure). To measure and/or control the supplied voltage and current two power supply systems were used. The capacity of each channel is 10 kW.

For the tests, the heat exchanging tube is assembled vertically at the supporter (Fig. 1(a)) and an auxiliary supporter (Fig. 1(c)) is used to fix a glass tube (Fig. 1(c)). To make the annular condition, three glass tubes ($s = 3.65$, 6.35, and 17.95 mm) of different axial length ($L_o = 0.2$, 0.3, 0.4, 0.5, and 0.6 m) were used. A fixture made of slim wires was inserted into the upper side of the gap to keep the space between the heating tubes. The assembled test section is shown in Fig. 1(d).

After the water storage tank is filled with water until the initial water level is reached at 1100 mm, the water is then heated using four pre-heaters at constant power. When the water temperature is reached at a saturation value (i.e., $T_{sat} = 100$ °C since all the tests are run at atmospheric pressure condition), the water is then boiled for 30 min to remove the dissolved air. The temperatures of the tube surface (T_W) are measured when they are at steady state while controlling the heat flux on the tube surface with input