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Effects of pool subcooling on boiling heat transfer in a vertical annulus with closed bottom

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Abstract

Effects of inlet subcooling on pool boiling heat transfer in a vertical annulus with closed bottom have been studied experimentally. For the test, a tube of 19.1 mm diameter and the water at atmospheric pressure have been used. Up to 50 K of pool subcooling has been tested and results of the annulus are compared with the data of a single unrestricted tube. The increase in pool subcooling results in much change in heat transfer coefficients. As the heat flux increases and the subcooling decreases, a deterioration of heat transfer coefficients is observed. The governing mechanisms are suggested as single-phase heat transfer and liquid agitation for the single tube while liquid agitation and bubble coalescence are the major factors at the bottom closed annulus.

1. Introduction

For the past several decades pool boiling heat transfer has been widely investigated. One of the possible fields of application is to design passive heat exchangers, which are major safety facilities in advanced light water reactors [1]. Among the design parameters two important subjects, from the viewpoint of safety and space, are (1) to evaluate effects of liquid subcooling on pool boiling heat transfer and (2) to find out a way of increasing heat transfer. Heat exchangers situated in a water storage tank is initially subcooled and the boiling mechanism on the tube surface is eventually changing from the subcooled to the saturated once the facilities got into operation.

There are many research results as the heated geometry is unrestricted in a narrow space. Judd et al. [2] investigated effects of subcooling on boiling heat transfer in nucleate boiling region. They studied theoretically the relation between the degree of subcooling and superheating through analyzing previous experimental results. Celata et al. [3] published some results of comparing pool and forced convective boiling. They selected binary mixtures and investigated effects of mixing ratio, subcooling, and fluid velocity. Recently, Kang [4] published some preliminary studies to investigate effects of subcooling on pool boiling heat transfer and thermal mixing by using a vertically installed stainless steel tube of 19.1 mm diameter and the water at atmospheric pressure.

Although the effect of subcooling on flow boiling in annuli has been widely studied [5,6], the study on subcooled pool boiling in annuli is very limited. Some previous results about crevice effects on pool boiling heat

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Nomenclature

A	heat transfer area	T_{sat}	saturation temperature
D	heating tube diameter	T_W	tube wall temperature
h_b	boiling heat transfer coefficient	T_{wat}	water temperature
I	supplied current	T_{wi}	water temperature in the annulus
L	tube length	V	supplied voltage
q	input power	ΔT_{sat}	tube wall superheating ($=T_W - T_{sat}$)
q''	heat flux	ΔT_{sub}	pool subcooling ($=T_{sat} - T_{wat}$)
t	time		

transfer are summarized in Table 1. As shown in the table major geometries concerning about the crevices are annuli [7–9] and plates [10–12]. Some geometry have closed bottom [7,9,10]. Through the literature survey, it can be concluded that studies about the effect of pool subcooling in annuli are very rare. Hung and Yao [8]

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

Authors	Remarks
Yao and Chang [7]	• 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 [8]	• 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
Fujita et al. [10]	• Heater: copper plate (30 × 30 and 30 × 120 mm in width × length) • Liquid: water at 1 atm • Liquidcondition: saturated • Geometry: – vertical and inclined spaces between rectangular surfaces – periphery; open, closed sides, closed sides and bottom • Gap sizes: 0.15, 0.60, 2.0 and 5.0 mm
Bonjour and Lallemand [11]	• Heater: copper plate (60 × 120 mm in width × length) • Liquid: R-113 at 1 atm • Liquid condition: saturated • Geometry: – vertical spaces between rectangular surfaces – periphery; sides and bottom are left open • Gap sizes: 0.3, 0.50, 1.0 and 2.0 mm
Kang [4]	• 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
Passos et al. [12]	• Heater: copper disk (diameter 12 mm) • Liquid: FC72 and FC87 at 1 atm • Liquid condition: subcooled or saturated • Geometry: horizontal spaces between disks • Gap sizes: 0.2, 0.5, 1.0, 2.0, and 13 mm

tested only 25 K of pool subcooling and suggested that, at same wall superheat, the heat flux is higher for subcooled boiling.

Summarizing the previous results, effects of subcooling on boiling heat transfer have been studied much as the fluid is in forced circulation and/or the heated geometry is not confined in a narrow space. Up to the author's knowledge, no previous results concerning about subcooled pool boiling in annuli with closed bottom have been published. Mechanisms of forced convective boiling are different from pool boiling [1] and the boiling mechanisms in a confined space are different from the unrestricted cases. Therefore, the present study is aimed at the investigation of subcooled pool boiling in a confined annular space with closed bottom, which is one of the effective ways to improve heat transfer at relatively lower heat fluxes.

2. Experiments

A schematic view of the present experimental apparatus and test sections is shown in Fig. 1. The water storage tank (Fig. 1(a)) is made of stainless steel and has a

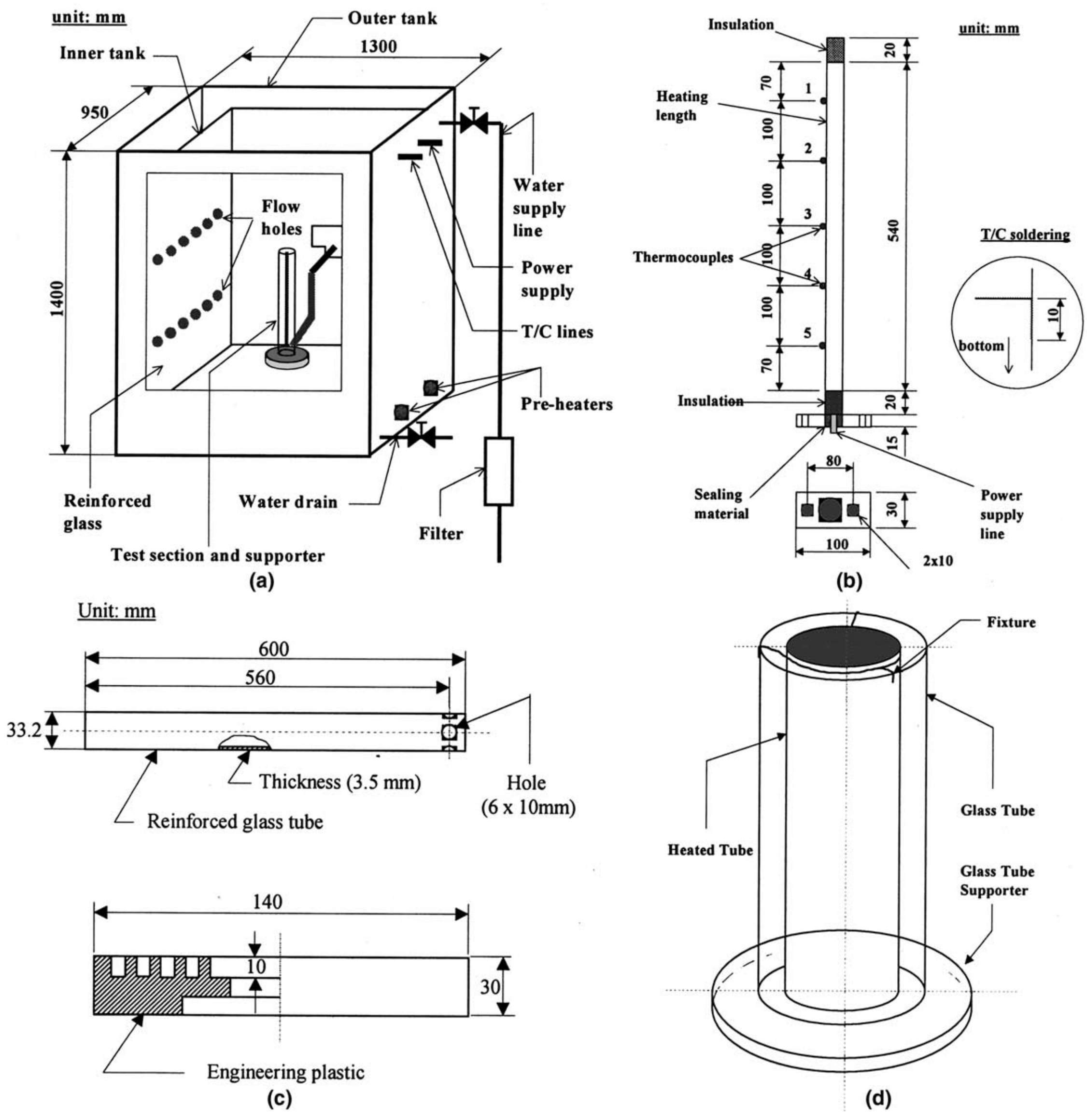

Fig. 1. Schematic diagram of the experimental apparatus.

rectangular cross section (950×1300 mm) and a height of 1400 mm. This tank has a glass view port (1000×1000 mm) which permits viewing of the tubes and photographing. The tank has a double container

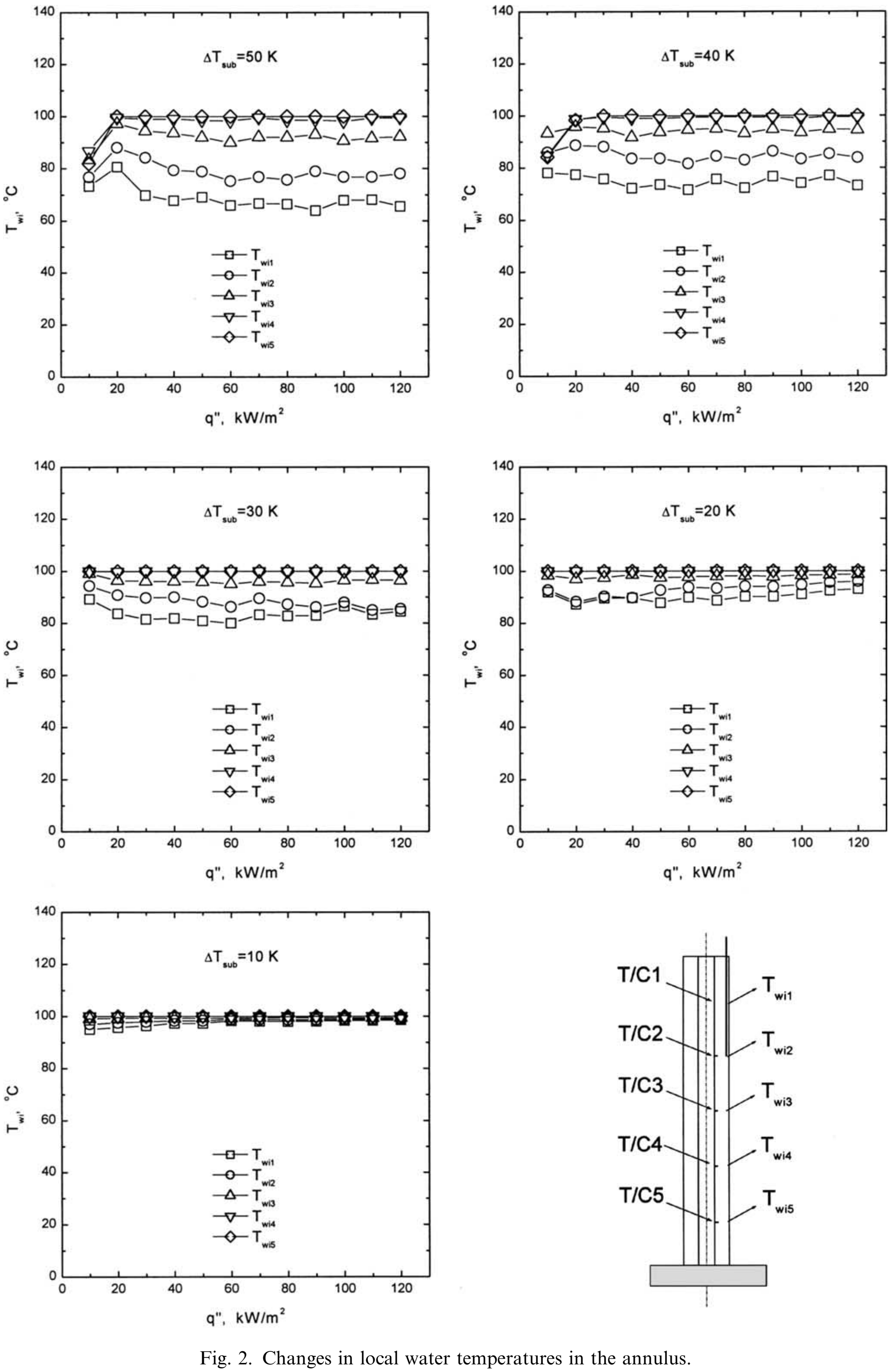

Fig. 2. Changes in local water temperatures in the annulus.

system. 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. To reduce heat loss to the environment, the left, right, and rear sides of the tank were insulated by glass wool of 50 mm thickness. The heat exchanger tubes are simulated by resistance heaters (Fig. 1(b)) made of a very smooth stainless steel tube (L = 540 mm 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-degree angle and the bent tip 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. 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 (each having three channels for reading of both voltage and current in digital values) 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(d)). To make the annular condition, a glass tube of 33.2 mm inside diameter was used. Therefore, the gap size of the annulus is 7.05 mm. A fixture made of slim wires was inserted into the upper side of the gap to keep the space between the heating tube and the glass tube.

After the water storage tank is filled with water until the initial water level is at 1100 mm from the outer tank bottom, the water is heated using four pre-heaters at constant power (5 kW/heater). Through the heating process, temperatures of the water were measured. When the water temperature reaches the required value, the supply of electricity to the heated tube started. Once a set of experiments has been performed for various heat fluxes at the fixed subcooling, a series of experiments has been executed for the different pool subcooling. The single tube has been tested at first, and then the annulus is tested.

The heat flux from the electrically heated tube surface is calculated from the measured values of the input power as follows:

$$q'' = \frac{q}{A} = \frac{VI}{\pi DL} = h_b \Delta T \quad (1)$$

$$\Delta T = T_W - T_{wat} \quad \text{single tube}$$
$$\Delta T = T_W - T_{wi} \quad \text{annulus}$$

where V and I are the supplied voltage (in volt) and current (in ampere), and D and L are the outside diameter and the length of the heated tube, respectively. T_W and T_{wat} represent the measured temperatures of the tube surface and water, respectively. Here, T_{wi} denotes the temperature of water in the annulus. Every temperatures used in Eq. (1) are the arithmetic average values of the temperatures measured by thermocouples. To determine T_W, time-averaged (for 90 s) local values have been arithmetically averaged.

The uncertainty in the heat flux is estimated to be ±1.0%. The measured temperature has uncertainties originated from the thermocouple probe itself, thermocouple brazing,and translation of the measured electric signals to digital values. The total uncertainty of the measured temperatures is estimated as ±0.3 K. The uncertainty in the heat transfer coefficient can be determined through the calculation of $q''/\Delta T$ and is within ±10%.

3. Results and discussion

To measure liquid temperatures in the annulus five thermocouples were inserted in the space between the

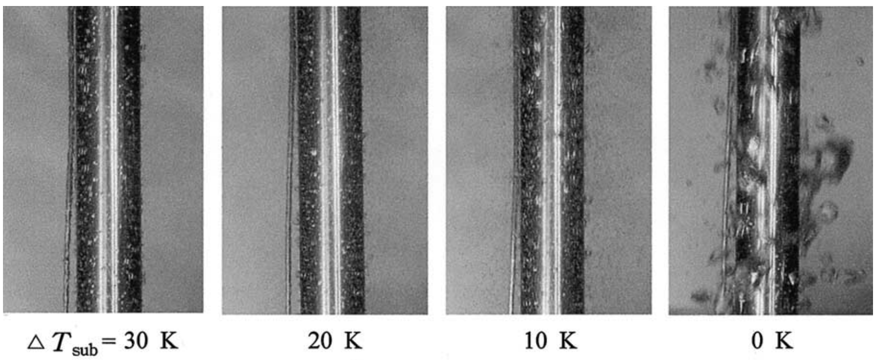

Fig. 3. Photos of boiling on the single tube surface at q'' = 70 kW/m^2.

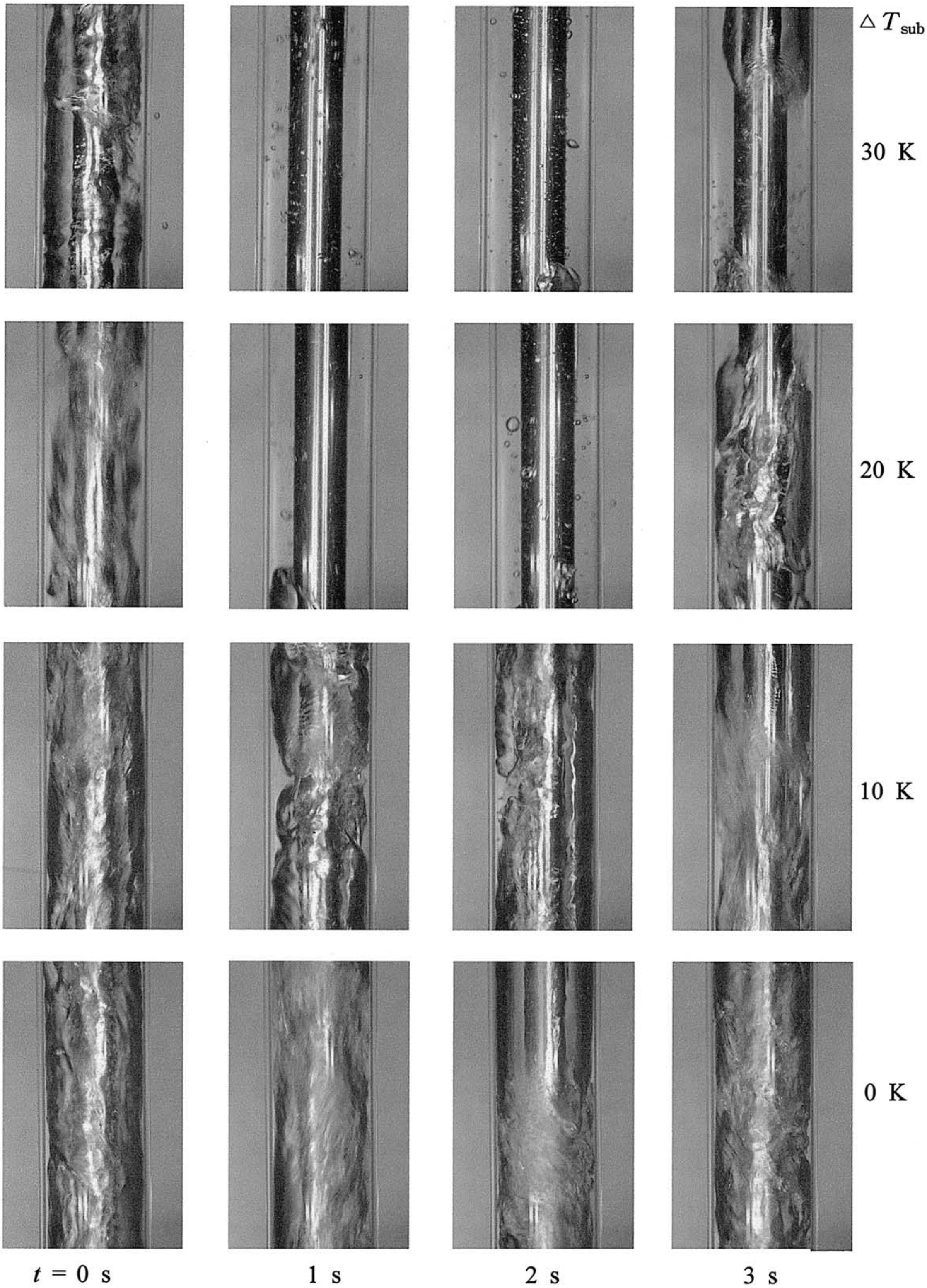

Fig. 4. Photos of subcooled boiling in the annulus at $q'' = 70\,kW/m^2$.

inside and the outside tubes. Since the measured temperatures are fluctuating much due to the discontinuous liquid inflow, the measured values for the first some seconds has been averaged. Fig. 2 shows the averaged local temperatures of the liquid in the space as the subcooling and the heat flux change. At $q'' \geqslant 20\,\mathrm{kW/m^2}$ the lowermost region (T_{wi5} is almost saturated regardless of the degree of inlet subcooling. The difference in temperature between the uppermost (T_{wi1}) and the lowermost (T_{wi5}) gets decreasing as the degree of subcooling decreases and the heat flux increases. To evaluate average water temperatures in the annulus local values shown in Fig. 2 have been arithmetically averaged.

For visual observation several photos of boiling on the surface have been taken and shown in the Figs. 3 and 4. Every photo was taken at the level of the thermocouple 2 of the heated tube. Several photos at $70\,\mathrm{kW/m^2}$ have been compared as the degree of subcooling increases from 0 to 30 K. For the single tube, sizes of the departed bubbles are tiny and the departed bubbles are almost collapsed before they reach the water surface at ΔT_{sub} is larger than 10 K. As ΔT_{sub} approaches to 0 K, sizes of bubbles on the surface are increasing and the departed bubbles move to the water surface. Therefore, it might be explained that the intensity of agitation due to the departed bubbles is almost negligible in the highly subcooled liquid and gets increased as the liquid becomes to be saturated. Since pool boiling in the annulus with closed bottom is not steady, but is frequent [9], several photos of boiling on the tube surface have been taken for the first 3 s and shown in the Fig. 4. As the degree of subcooling gets lower the bubble bunches are more frequently observed in the space. Big bunches of bubbles are observed even at lower subcooling. Only small bubbles are observed at first and, then, sudden creation of many bubbles is started from the bottom region

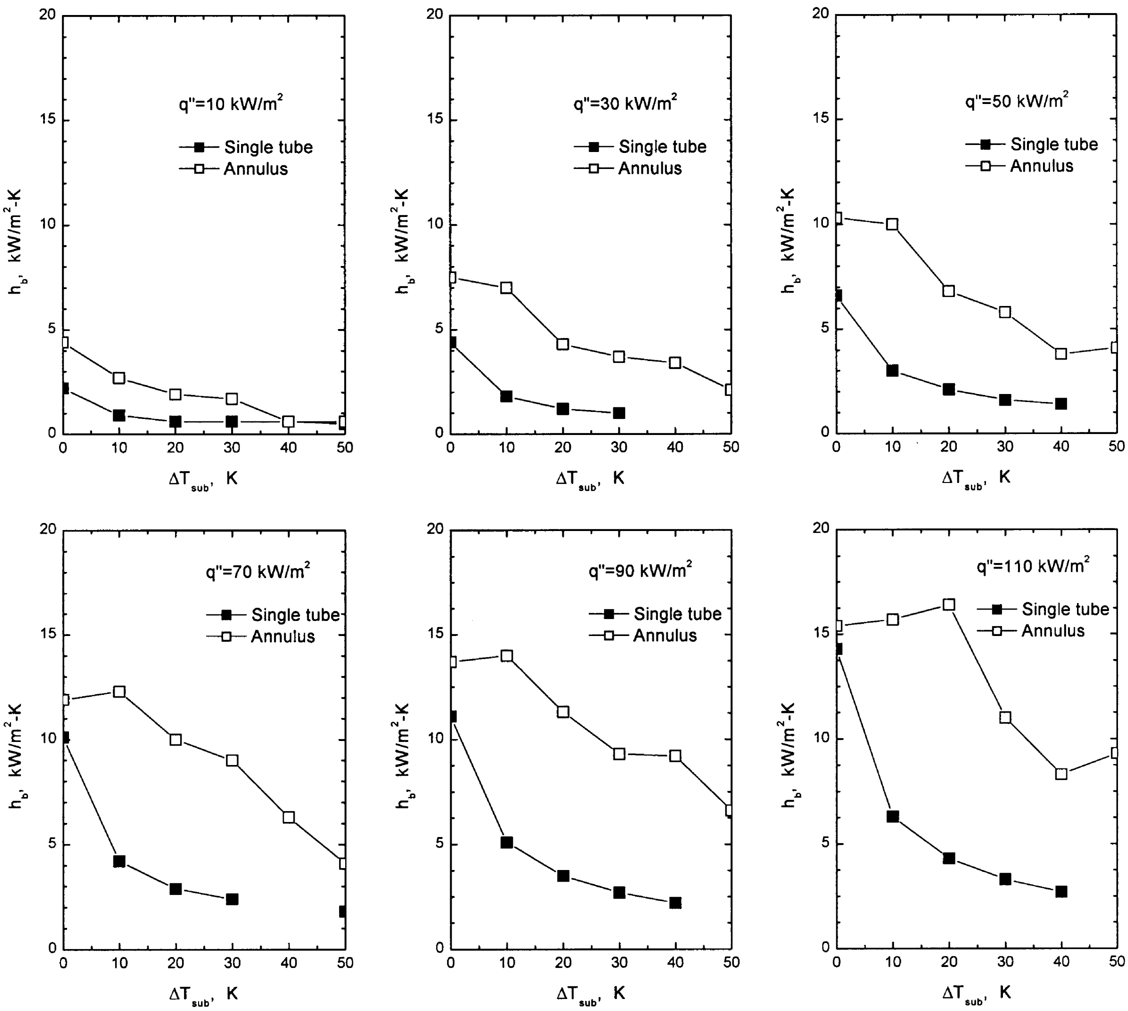

Fig. 5. Variations in heat transfer coefficients as the degree of subcooling changes.

of the tube. The bubbles generate big slugs in the space and move to the upper end side sweeping over the heated tube surface. After the bubble slugs escaped from the space there would be abrupt liquid rush to the space from the environment. As the temperature of the liquid increases nearby the saturation value, sudden creation of bubbles is starting again. This series of procedure generates a kind of pulsating flow of bubbles and liquid in the annular space. Therefore, very active agitation is expected at the annulus with closed bottom. The period depends on the heat flux and subcooling. Higher subcooling and lower heat fluxes result in longer time of oscillating. As the degree of subcooling is decreased, the generation of bubbles gets more frequent and, then, the bubble slugs cover almost every space in the annulus. It can be suggested that the dominant heat transfer mechanism is closely related with the active agitation at highly subcooled region. Thereafter, the mechanism changes to bubble coalescence on the surface as the liquid in the pool gets saturated.

Fig. 5 shows changes in heat transfer coefficients as the degree of pool subcooling changes. Both results of the single tube and the annulus are depicted at the same heat flux. The increase in pool subcooling results in much decrease in heat transfer coefficients. As ΔT_{sub} decreases from 50 to 0 K at $q'' = 70\,kW/m^2$, 461 % (from 1.8 to 10.1 kW/m^2K) and 190 % (from 4.1 to 11.9 kW/m^2K) increases in heat transfer coefficients are observed for the single tube and the annulus, respectively. For the single tube heat transfer coefficients are decreasing almost linearly as $\Delta T_{sub} > 10\,K$. At these regions the single-phase heat transfer is the major mechanism as Judd et al. [2] suggested. However, as $\Delta T_{sub} \leqslant 10\,K$ the heat transfer coefficients increase suddenly and the governing mechanism changes to the active liquid agitation followed after the increase in the nucleation sites density. The annulus with closed bottom is different from the single tube. The deterioration of heat transfer coefficients is observed as the degree of subcooling decreases. This denotes the existence of bubble coalescence on the surface as observed in Fig. 4. At lowest heat flux ($10\,kW/m^2$), since there are no enough bubble bunches to cover the surface, no deterioration is shown and the coefficient increases gradually due to the increase in the intensity of liquid agitation followed by the increase in nucleation sites. Earlier deterioration of the heat transfer coefficient is observed at $q'' > 30\,kW/m^2$. At highly subcooled region very active agitation is expected and the coefficients are much larger than the single tube.

To identify changes in heat transfer coefficients due to the annulus coefficients of the annulus have been compared with the values of the single tube and the ratio of $h_{b,annulus}/h_{b,single}$ is depicted in Fig. 6. As $10\,K \leqslant \Delta T_{sub} \leqslant 30\,K$ the ratio is between 3 and 4. At $\Delta T_{sub} = 0\,K$ the ratio decreases almost linearly (from 2 to 1) as the heat flux increases (from 10 to 110 kW/m^2). The most dramatic change in the ratio is observed at $\Delta T_{sub} = 40\,K$. This denotes the rapid increase in the intensity of active liquid agitation, as q'' is less than $90\,kW/m^2$. Thereafter, the ratio decreases to show the change in the governing mechanism to the bubble coalescence.

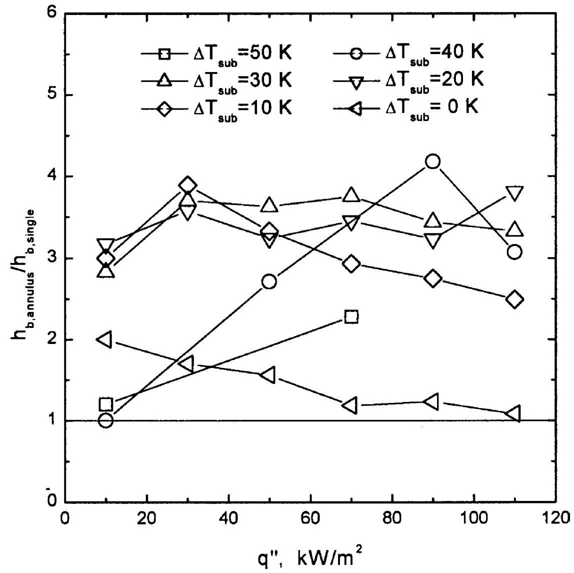

Fig. 6. Ratio of $h_{b,annulus}/h_{b,single}$ as ΔT_{sub} and q'' change.

4. Conclusions

To identify effects of liquid subcooling on pool boiling heat transfer of water at atmospheric pressure, the vertical annulus with closed bottom has been studied experimentally. In addition, the results were compared with those of the unrestricted single tube. The major conclusions of the present study are as following:

1. The increase in liquid subcooling results in much change in the heat transfer coefficient. As ΔT_{sub} decreases from 50 to 0 K at $q'' = 70\,kW/m^2$, 461 % (from 1.8 to 10.1 kW/m^2K) are observed for the single tube.
2. At the annuli with closed bottom higher heat transfer coefficients are observed at higher subcooling. However, a deterioration of heat transfer coefficients is observed as the degree of subcooling decreases.
3. The major heat transfer mechanisms for the single tube suggested as single-phase heat transfer and liquid agitation at $\Delta T_{sub} > 10\,K$ and $\Delta T_{sub} \leqslant 10\,K$, respectively. For the annulus with closed bottom liquid agitation is the governing mechanism at $\Delta T_{sub} > 10\,K$ and the governing mechanism changes to bubble coalescence at $\Delta T_{sub} \leqslant 10\,K$.

Acknowledgment

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