Effects of Inclination Angle on Pool Boiling Heat Transfer of Near Horizontal Tubes

Myeong-Gie Kang *
Department of Mechanical Engineering Education, Andong National University
388 Songchun-dong, Andong-city, Kyungbuk 760-749
**Corresponding author: mgkang@anu.ac.kr*

1. Introduction

Pool boiling heat transfer has been studied for the past decades to guarantee the inherent safety of industrial systems. Recently, a passive type heat exchanger has been adopted in nuclear power plants to meet safety functions in case of no power supply [1,2]. One of the major issues in pool boiling is the inclination angle (θ) of a heated surface [3]. Many researchers have investigated the inclined surface for the various combinations of geometries and liquids as listed in Table 1.

Table 1. Summary of Previous Investigations [3]

Author	Geometry	Liquid	Parameters
El-Genk & Bostanci	Flat plate	HFE-7100	θ=0°-180°
Stralen & Sluyter	Wire	Water	θ=0°,90°
Nishikawa et al.	Flat plate	Water	θ=0°-175°
Jung et al.	Flat plate	R-11	θ=0°-180° Enhanced surface
Fujita et al.	Parallel plates	Water	θ=0°-175° Gap size Flow area confinement
Sateesh et al.	Single tube	Water Ethanol Acetone	θ=0°-90° Diameter Surface roughness
Narayan et al.	Single tube	Nano fluid	θ=0°-90° Particle concentration
Kang	Single tube Annulus	Water	θ=0°-90° Flow confinement
Kang	Tube inside	Water	θ=0°-90°

Many researchers have investigated the effect of inclination angle on pool boiling heat transfer along with the effects of pressure and fluid properties for the past decades. However, there are remaining areas to be identified. One of them is its effect on pool boiling heat transfer of nearly horizontal tubes. The passive condensers adopted in 'Siedewasserreaktor' (SWR, German: boiling water reactor) 1000 [4] and the advanced power reactor plus (APR+) are slightly inclined from the horizontal position to prevent the occurrence of water hammer [2].

Since the movement of the bubbles on the inclined surface is different from the horizontal one, to identify its effect is of interest. Although there are lots of studies introducing results for the effects of inclination angle on pool boiling heat transfer [3], no results are treating this issue. Therefore, the present study is aimed at the identification of the effect of the inclination angle on pool boiling heat transfer of nearly horizontal tubes.

2. Experiments

For the tests, the assembled test section (Fig. 1) was located in a water tank which had a rectangular cross section (950×1300 mm) and a height of 1400 mm. The heat exchanging tubes are resistance heaters made of stainless steel. The tube was finished through a buffing process to have a smooth surface. The arithmetic mean of all deviations from the center line over the sampling path has the value of R_a =0.15μm. Electric power of 220 V AC was supplied through the bottom side of the tube.

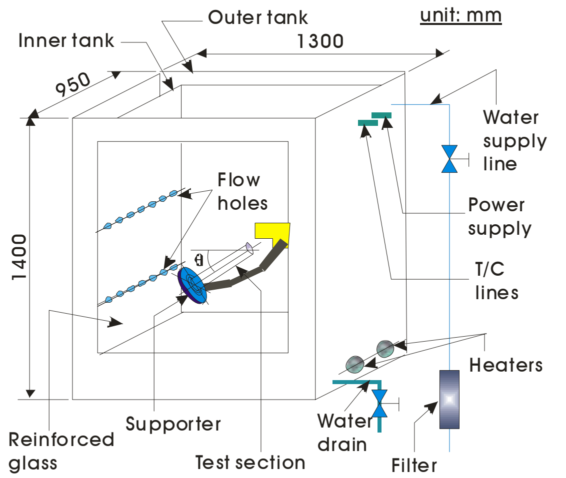

Fig. 1. Schematic of experimental apparatus.

The tube outside was instrumented with T-type sheathed thermocouples. The thermocouples were brazed on the sides of the tube. The water temperatures were measured with six sheathed T-type thermocouples 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, power supply systems were used.

Table 2. Test Matrix

D, mm	L, mm	L/D	θ, °
19	400	21.05	0°, 1°, 3°, 5°, 7°, 9°
19	540	28.42	0°, 3°, 6°, 12°
50.8	300	5.91	0°, 3°, 6°, 9°

The inclination angle was regulated by adjusting the supporter. The inclination angle (shown in Fig. 1) of a tube was varied from 0° to 12°. For the tests two tube diameters (D) and three tube lengths (L) were considered as listed in Table 2.

After the water tank was filled with water until the initial water level reached 1.1 m, the water was then heated using four pre-heaters at constant power. When the water temperature was reached the saturation value, the water was then boiled for 30 minutes to remove the dissolved air. The temperatures of the tube surfaces were measured when they were at steady state while controlling the heat flux (q'') on the upper tube surface with input power.

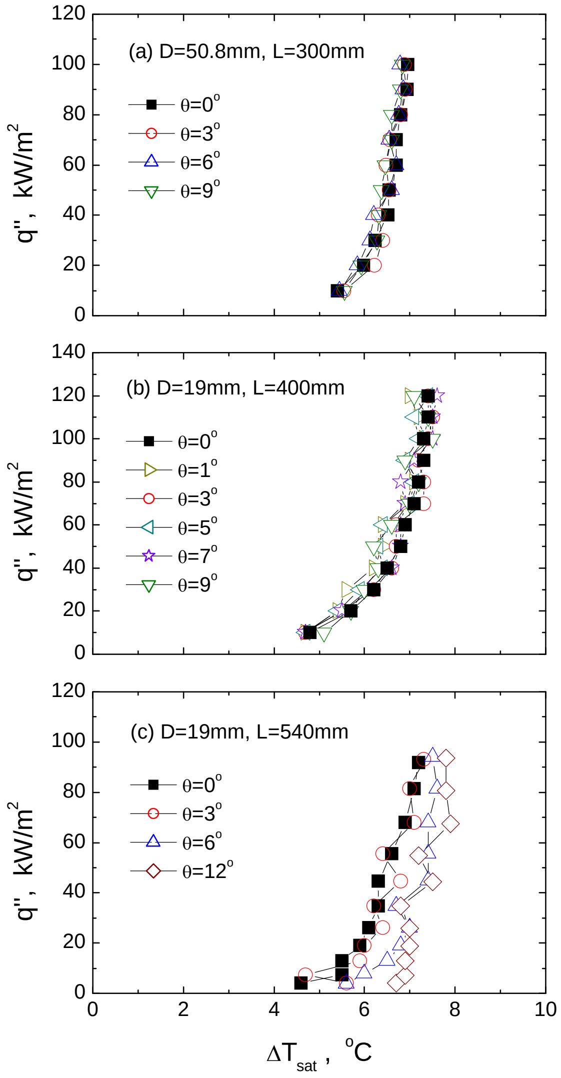

Fig. 2. Plots of experimental data.

The uncertainties of the experimental data were calculated from the law of error propagation [5]. The uncertainty of the measured temperature had the value of ±0.11°C. The uncertainty in the heat flux was estimated to be ±0.7%. Since the heat transfer coefficient (h_b) was the value of the heat flux divided by the tube wall superheating (ΔT_{sat}), a statistical analysis on the results was performed. After calculating and taking the mean of the uncertainties of the propagation errors, the uncertainty of the heat transfer coefficient was determined to be ±6%.

3. Results

Figure 2 shows plots of heat flux versus tube wall superheat for the various inclination angles. Two tube diameters (i.e., 19 and 50.8mm) and three tube lengths (i.e., 300, 400, and 540mm) were tested to obtain the combined effects of the diameter and length of the tube with the inclination angle. The effect of the inclination angle on heat transfer is not very obvious. The tendency is dependent on the L/D values. The values of L/D are 5.91, 21.05, and 28.42 for the tubes of Fig. 2(a), (b), and (c), respectively. As the value of L/D increases, the effect of the inclination angle is increasing.

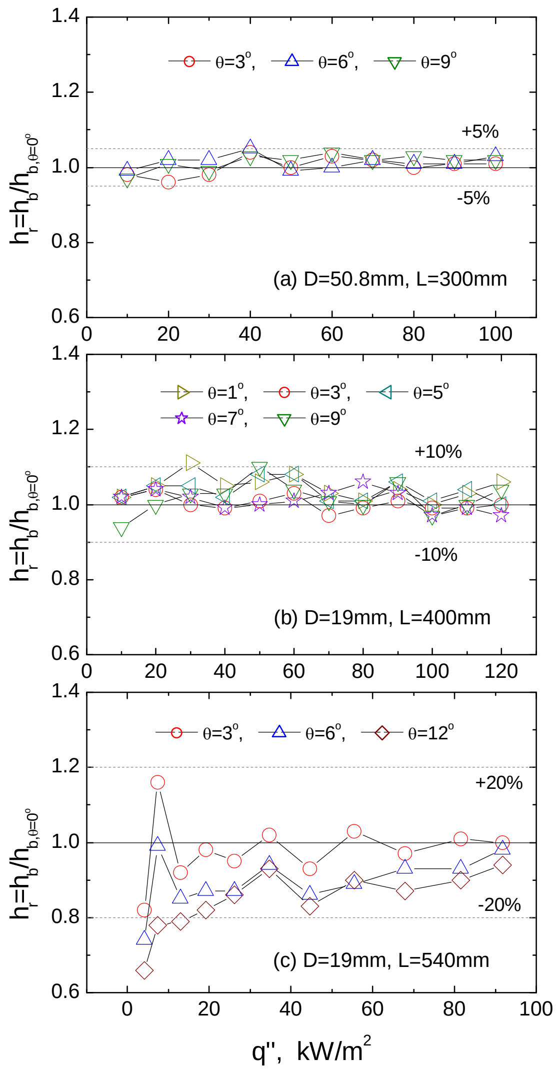

Fig. 3. Curves of $h_b / h_{b,\theta=0^\circ}$ versus heat flux.

The ratios of $h_b / h_{b,\theta=0°}$ were plotted against the heat flux to identify the variation of heat transfer due to the tube geometry for the various inclination angles. $h_{b,\theta=0°}$ is the heat transfer coefficient for the horizontal tube. The results are as shown in Fig. 3. The ratios are in the range of 5%~20%. The increase of the inclination angle is increasing or decreasing the ratio depending on the L/D value. The effect of the surface configuration is remarkable at low heat fluxes as Nishikawa et al. [6] noticed. However, the ratios are converging to 1 as the heat flux increases.

The mechanisms of liquid agitation, bubble coalescence, and the length of bubble traveling along the tube surface were considered for heat transfer. Liquid agitation increases heat transfer, whereas bubble coalescence decreases heat transfer. The length of bubble traveling along the tube surface increases or decreases heat transfer depending on the intensity of liquid agitation. The increase of the inclination angle also increases the length of bubble traveling. Therefore a distinct change of $h_b / h_{b,\theta=0°}$ is observed in Fig. 3 when θ is large. As the length of bubble traveling is increasing, the intensity of liquid agitation is changed.

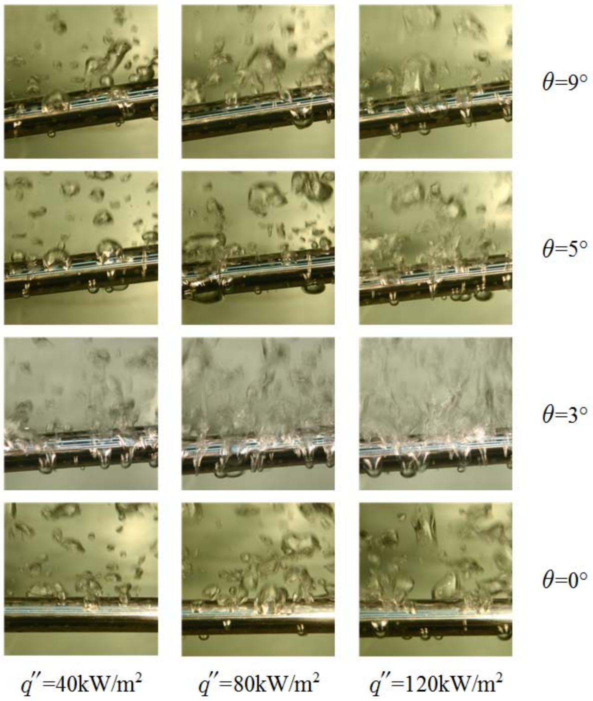

Fig. 4. Photos of pool boiling for L/D=21.05.

The intensity of liquid agitation is weak at low heat fluxes. At these heat fluxes the intensity is highly dependent on the sliding bubbles [7] along the tube surface. Therefore a low value of $h_b / h_{b,\theta=0°}$ is observed. As the heat flux increases, the intensity of liquid agitation increases due to the generation of turbulence by the departed bubbles. This enhances heat transfer. The intensity of liquid agitation is relatively weak when the inclination angle is small. The increase of the heat flux also increases the effect of bubble coalescence on heat transfer. This phenomenon deteriorates heat transfer. Some photos of pool boiling are as shown in Fig. 4.

3. Conclusions

To identify the effect of the inclination angle on pool boiling heat transfer of a nearly horizontal tube three tubes having L/D = 21.05, 28.42, and 5.91, respectively, were studied. As the value of L/D increases, the effect of the inclination angle is increasing. The increase of the inclination angle is increasing or decreasing the heat transfer depending on the L/D value. However, the ratio of $h_b / h_{b,\theta=0°}$ is converging to 1 as the heat flux increases. The mechanisms of liquid agitation, bubble coalescence, and the length of bubble traveling along the tube surface were considered as the major factors for heat transfer.

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