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Effects of inclination angle on pool boiling heat transfer of near horizontal tubes

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ABSTRACT

An experimental study is performed to identify the effect of inclination angle on pool boiling heat transfer of a nearly horizontal tube. For the test, three stainless steel tubes having a smooth surface and the water at atmospheric pressure are used. The effect of inclination angle, ranging from 0° to 12°, on heat transfer depends on the ratio of the length divided by the diameter of a tube. The inclination angle changes the amounts of liquid agitation and bubble coalescence. A distinct change in heat transfer is observed when the inclination angle and the ratio have higher values. To evaluate the inclination effect on heat transfer an empirical correlation, which predicts the experimental data within ± 10%, is newly suggested.

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 advanced nuclear power plants to meet safety functions in case of no power supply [1,2]. One of the major issues 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.

Chun and Kang [1] identified that the inclination angle, as well as the surface roughness, changed heat transfer. Stralen et al. [5] said that the horizontal type showed enhanced heat transfer than the vertical wires. According to Nishikawa et al. [6], boiling heat transfer is distinct at low heat flux regions less than 100 kW/m^2. Narayan et al. [10] identified that the addition of nanoparticles varied the tendency of heat transfer curves for the various inclination angles. The narrower gap size between two plates could decrease the heat transfer for the given inclination angle [8]. Kang [11,12] performed experiments for a tube, an annulus, and the inside surface of a circular tube and identified that the inclination angle results in much change in pool boiling heat transfer.

El-Genk and Suszko [13] also studied the effect of inclination angle on pool boiling heat transfer of dielectric liquid for application to the cooling of power computer chips. Recently, some studies were performed to identify the inclination effect on pool boiling were done using a disk [14], a plate [15], and a single tube [16] for the thermal design of advanced nuclear reactors. The authors suggest that the inclination changes much in heat transfer at low heat fluxes. Amidu et al. [16] performed to identify the effect of inclination on both pool boiling and condensation. Dajoo et al. [17] performed a test for both nanofluid and water and identified that the heater orientation shows a dramatic effect on pool boiling due to the coalescing bubbles.

Although many researchers have in the past decades investigated the effect of the inclination angle, pool boiling heat transfer on nearly horizontal tubes are still needed more study. The passive condensers adopted in 'Siedewasserreaktor' (SWR, German: boiling water reactor) 1000 [18] and the advanced power reactor plus (APR +) [2] are slightly inclined from the horizontal position to prevent the occurrence of water hammer as shown in Fig. 1.

Since the movement of the bubbles on the inclined surface is different from the horizontal one, to identify its effect is of interest. Although many researchers studied the effects of the inclined surface on pool boiling heat transfer [3], the results for the nearly horizontal tubes are very rare. Therefore, the present study is investigating the effect of the inclination angle on pool boiling of nearly horizontal tubes.

2. Experiments

The assembled test section (Fig. 2) is situated in a water tank having a rectangular cross-section (950 × 1300 mm) and a height of 1400 mm. The tank is a double container system. The size of the inner tank is 800 × 1000 × 1100 mm (depth × width × height). The bottom side of the inner tank is situated 200 mm above the bottom of the outer one. There are several flow holes (28 mm in diameter) on the wall of the inner tank to allow fluid inflow from the outer one. The holes are situated at the height of 300 and 800 mm from the bottom of the inside tank to diminish the inflow effect on the inside water. The upside of the

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Table 1
Summary of previous investigations.

Author	Geometry	Liquid	Parameters
El-Genk & Bostanci [4]	Flat plate	HFE-7100	θ = 0–180°
Stralen & Sluyter [5]	Wire	Water	θ = 0°, 90°
Nishikawa et al. [6]	Flat plate	Water	θ = 0–175°
Jung et al. [7]	Flat plate	R-11	θ = 0–180° Enhanced surface
Fujita et al. [8]	Parallel plates	Water	θ = 0–175° Gap size Flow area confinement
Sateesh et al. [9]	Single tube	Water Ethanol Acetone	θ = 0–90° Diameter Surface roughness
Narayan et al. [10]	Single tube	Nano fluid	θ = 0–90° Particle concentration
Kang [11]	Single tube Annulus	Water	θ = 0–90° Flow confinement
Kang [12]	Tube inside	Water	θ = 0–90°
El-Genk & Suszko [13]	Flat plate	PF-5060	θ = 0–180°
Mei et al. [14]	Flat disk	Water	θ = 0–180° Heater material
Jung & Kim [15]	Flat plate	Water	θ = 0–90°
Amidu et al. [16]	Single tube	Water	θ = 0–90°
Dadjoo et al. [17]	Flat plate	Nano fluid	θ = 0–90° Surface roughness

water storage tank is covered with two stainless steel plates to minimize the loss of the water as small as possible while the water boils. To maintain the atmospheric pressure small area is opened to the atmosphere. Most of the evaporated vapor condenses on the downward surface of the upside cover and returns to the water surface. Only a small amount of the vapor escapes from the water tank, and its effect on the pool boiling is negligible.

The heat exchanging tubes are resistance heaters made of stainless steel. A few strands of electric resistance wire are located inside the heated tube to supply electric power. Moreover, insulation powder is packed into the space between the tube inside wall and the wires to prevent any possible current flowing to the data acquisition system through the thermocouple lines. The surface of the tube is finished through buffing process to have very smooth surface. The surface of the tube is processed by a buffing machine. The value of the surface roughness is R_a = 0.15 μm. For the test, the electric supply of 220 V AC to the tube is done.

The temperatures of the tube are instrumented by T-type sheathed thermocouples. The thermocouples are brazed on the sides of the tube as shown in Fig. 3. The six sheathed T-type thermocouples are used to measure water temperature. The thermocouples are placed vertically at a corner of the inside tank. All tests are performed at atmospheric pressure. Three power supply systems are used to measure and control the supplied voltage and current. The inclination angle is regulated by adjusting the supporter. The inclination angle of a tube is varied from 0° to 12° as shown in Fig. 2. For the tests, two diameters (D) and three lengths (L) of a tube are considered as listed in Table 2.

When the initial water level reached 1.1 m, the water is heated using four pre-heaters. After the water is saturated, additional 30 min boiling is continued to remove the dissolved air. The heat flux (q'') of the upper tube is controlled using the supplied electric power. The temperatures of the tube surfaces are measured when they are at steady state.

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

$$q''_T = \frac{VI}{\pi DL} = h_b \Delta T_{sat} = h_b (T_W - T_{sat}) \tag{1}$$

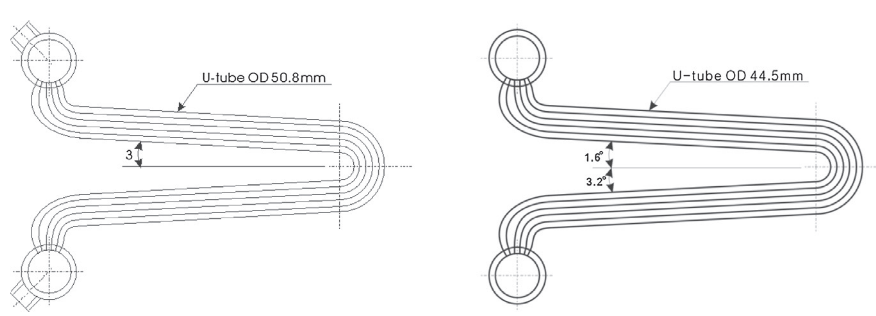
where V and I are the supplied voltage and current, and D and L are the outside diameter and the length of the heated tube, respectively. T_W and T_{sat} represent the measured temperatures of the tube surface and the saturated water, respectively. The temperatures used in Eq. (1) are an arithmetic average value of the measured temperatures.

The experimental uncertainty is analyzed by the law of error propagation [19]. The data acquisition error (A_T, ± 0.05 K) and the precision limit (P_T, ± 0.1 K) have been counted for the uncertainty analysis of the temperature. The 95 percent confidence uncertainty of the measured temperature is calculated from $(A_T^2 + P_T^2)^{1/2}$ and has the value of ± 0.11 K. The error bound of the voltage and current meters used for the test is ± 0.5% of the measured value. Therefore, the uncertainty of the calculated power (voltage × current) is ± 0.7%. Since the heat flux has the same error bound as the power, the uncertainty in the heat flux is estimated to be ± 0.7%. Since the uncertainty of the tube diameter and the length is ± 0.1 mm and its effect on the area is negligible. Therefore, the error of the heat transfer area is not counted when evaluating the uncertainty of the heat flux. To determine the uncertainty of the heat transfer coefficient the uncertainty propagation equation applies to the Eq. (1). A statistical analysis of the heat transfer coefficients results from the calculation of $q''/\Delta T_{sat}$ is performed. After calculation and taking the mean of the uncertainties of the propagation errors the uncertainty of the heat transfer coefficient can be decided as ± 6%.

3. Results

Fig. 4 shows plots of q'' versus ΔT_{sat} data obtained from the experiments. The inclination angle is changed from θ = 0° to 12° for L/D = 28.42 (L = 540 mm/D = 19 mm). As shown in the figure the heat transfer of the tube is deteriorated compared with the horizontal tube (i.e., θ = 0°) as the inclination angle increases. The change of the angle from 0° to 12° results in 19% (from 6.3 to 7.5 K) increase of ΔT_{sat} when q'' = 45 kW/m^2. Throughout the heat fluxes, the deterioration in heat transfer is observed clearly at low or moderate heat fluxes. As the heat flux increases, the difference of ΔT_{sat} between the inclination angles becomes decreasing. The curves for the inclined tubes converge to the curve for the horizontal tube when the heat flux is around 100 kW/m^2.

The ratios of $h_b/h_{b,\theta=0°}$ are plotted against the heat flux to identify the variation of heat transfer depending on the value of L/D for the



(a) APR+ Passive Condensation Heat Exchanger (b) SWR1000 Emergency Condenser

Fig. 1. Schematic diagram of passive type heat exchangers.