Transition Temperature to Enhance Heat Transfer in Subcooled Pool Boiling

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1. Introduction

One of the most effective ways to improve current pressurized water reactors is to adopt passive decay heat removal systems for the purpose of long-time core cooling without any external power supply and operator action. In the systems, water and/or steam circulate naturally to prevent core melting [1,2]. One of the most important facilities for the system is a passive heat exchanger that transfers core decay heat to the cold water in the water storage tank under atmospheric pressure.

Since the water in the tank is subcooled initially, it takes several hours to reach the saturation temperature. Therefore, the assumption of the saturated water for the initial tank condition could result in erroneous results. According to Judd et al. [3] heating surface temperature can be increased due to active site density decrease in subcooled liquid state. This means that the temperature of the tube inside (the primary side of the nuclear power plant in the present) is also increased, and this increase could be a cause of DNB (departure from nucleate boiling) at the surface of the fuel bundles in a nuclear reactor. Therefore, it is necessary to obtain a proper heat transfer coefficient (h_b) during the heating period to avoid a severe accident due to the increase of the water temperature in the primary side.

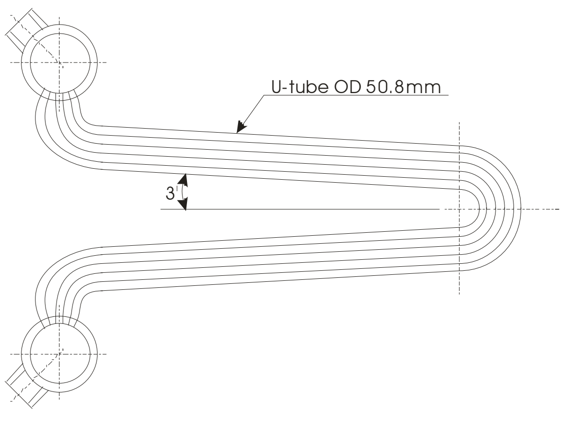

Fig. 1. Schematic view of PCHX in APR+ passive auxiliary feedwater system (PAFS).

The passive condensation heat exchanger (PCHX) adopted in APR+ has U-type tubes [4]. The PCHX is submerged in the passive condensation cooling tank (PCCT). The heat exchanging tubes are in vertical alignment and inclined at 3 degrees to prevent water hammer as shown in Fig. 1. For the cases, the upper tube is affected by the lower tube. Therefore, the results for a single tube are not applicable to the design of the PCHX. The water temperature in the PCCT rises according to the PAFS actuation and reaches the saturation temperature after more than 2.5 hours [4]. Since this period is very important to maintain reactor integrity, the exact evaluation of heat transfer on the tube bundle is indispensable.

The upper tube within a tube bundle can significantly increase nucleated boiling heat transfer compared to the lower tubes at moderate heat fluxes. Since the source of the convective flow in pool boiling is the lower heated tube, the heat flux of the lower tube (q''_L) is of interest. Recently, Kang [5] carried out an experimental parametric study of tandem tubes under saturated pool boiling condition to determine the effects of the tube pitch, elevation angle, and the heat flux of the lower tube on heat transfer.

An experimental study on subcooled pool boiling for application to APR+ was performed by Kang [2,6]. Kang was rewriting the temperature difference between the tube surface and the water ($\Delta T = T_W - T_{wat}$) as the tube wall super wall ($\Delta T_{sat} = T_W - T_{sat}$) plus the degree of liquid subcooling ($\Delta T_{sub} = T_{sat} - T_{wat}$). This expression is very useful when determining the major active mechanism in subcooled pool boiling.

As observed by Kang [6], there is a temperature that enhancing heat transfer. This temperature is decided at the point when ΔT_{sat} is larger than ΔT_{sub}. To obtain the temperature is important because a sudden variation in the heat transfer coefficient is observed around this temperature. Therefore, the present study is aimed to determine the transition temperature ($\Delta T_{transition}$) to activate pool boiling in the subcooled water at atmospheric pressure. Up to the author's knowledge, no previous results concerning this subject have been published yet. The results of this study could provide a clue to the thermal design of the PCHX.

2. Experiments

For the tests, the assembled test section (Fig. 2) was located in a water tank which had a rectangular cross section (950×1300 mm) and a height of 1400 mm as shown in Fig. 3. The heat exchanging tube is a resistance heater made of a very smooth stainless steel tube of 19 mm outside diameter (D) and 400 mm heated length (L). The tube was finished through a buffing process to have a smooth surface (roughness: R_a =0.15μm).

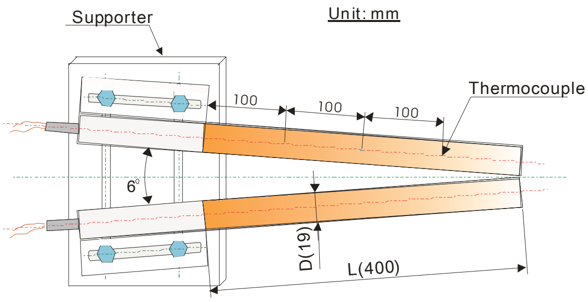

Fig. 2. Assembled test section.

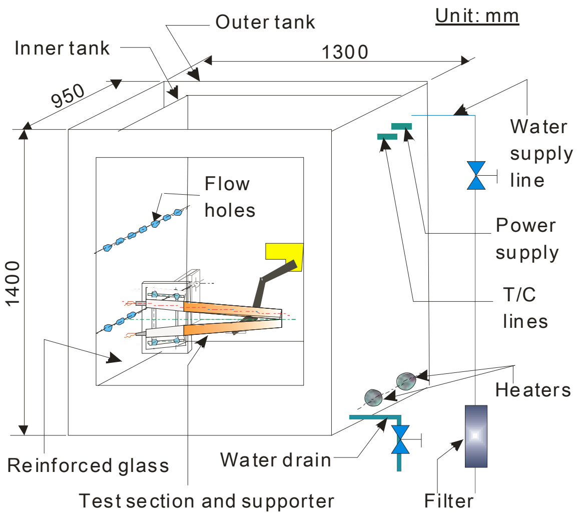

Fig. 3. Schematic of experimental apparatus.

The included angle was set as 6°. The heat flux of the lower tube was set a fixed value of 0, 30, 60, and 90 kW/m^2. The water tank was filled with the filtered tap 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 at a proper value, the power supply to the test section was activated. The heat flux on the test section (q''_T) was fixed (i.e., 30, 60, 90, and 120 kW/m^2) and heating of the water was started until it got saturated. The temperatures of the tube surfaces (T_W) and the water (T_{wat}) were measured through the heating process. Once a test for a set of q''_L and q''_T was completed, the liquid was cooled down lower than 50 °C. Then another set of heat fluxes was tested.

The tube outside was instrumented with six T-type sheathed thermocouples (diameter is 1.5 mm). The thermocouple tip (about 10 mm) was brazed on the sides of the tube wall. The water temperatures were measured with six sheathed T-type thermocouples attached to a stainless steel tube that placed vertically in a corner of the inside tank. All thermocouples were calibrated at a saturation value (100 °C since all tests are done at atmospheric pressure). To measure and/or control the supplied voltage and current, two power supply units were used.

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

$$q''_T = \frac{VI}{\pi DL} = h_b \Delta T = h_b (T_W - T_{wat}) \quad (1)$$

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_{wat} represent the measured temperatures of the tube surface and the water, respectively. Every temperature used in Eq. (1) is the arithmetic average value of the temperatures measured by the thermocouples.

The uncertainties of the experimental data were calculated from the law of error propagation [7]. The 95 percent confidence, uncertainty of the measured temperature has the value of ±0.11 °C. The uncertainty in the heat flux was estimated to be ±0.7%. Since the values of the heat transfer coefficient were the results of the calculation of $q''_T / \Delta T$, a statistical analysis of 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 4 shows plots of ΔT_{sat} versus ΔT_{sub} data for q''_L =30kW/m^2. The wall superheat increases for a while and, then, decreases as the degree of liquid subcooling increases. The value of ΔT_{sat} is increasing gradually until ΔT_{sub} reaches 8.4 °C at q''_T =60 kW/m². Then, ΔT_{sat} decreases as ΔT_{sub} increases. This tendency is similar to Judd et al.'s results [3]. The increase of q''_T results in the increase of ΔT_{sat} at a fixed ΔT_{sub} .

The ΔT shown in Eq. (1) can be rewritten as $\Delta T_{sat} + \Delta T_{sub}$. That is, $h_b = q''/(\Delta T_{sat} + \Delta T_{sub})$. The values of ΔT_{sat} and ΔT_{sub} represent the conditions of the tube surface and the water, respectively. The increase of ΔT_{sat} enhances the generation of bubbles whereas the increase in ΔT_{sub} suppresses the generation of bubbles. As the liquid becomes saturated h_b increases suddenly and, then, the value of $\Delta T_{sat} + \Delta T_{sub}$ decreases accordingly. The relation between the differences in temperatures and the heat transfer coefficient is shown in Fig. 5.

The turning point of the curves of ΔT_{sat} against ΔT_{sub} is closely related to the heat transfer enhancement. The wall superheat and the degree of liquid subcooling are same at the turning point as shown in Fig. 4 and 5. At the turning point the generation of bubbles changes suddenly (i.e., activating or suppressing). The activation of bubbles is enhancing the heat transfer. Therefore, the difference in temperatures at the turning point is named as a transition temperature.

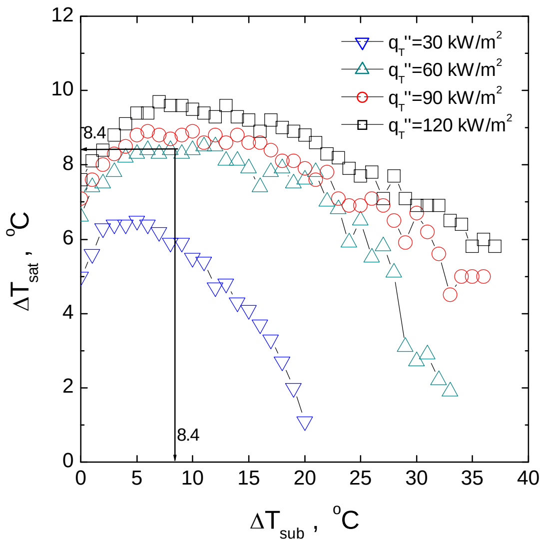

Fig. 4. Plots of ΔT_{sat} against ΔT_{sub} at q''_L =30kW/m^2.

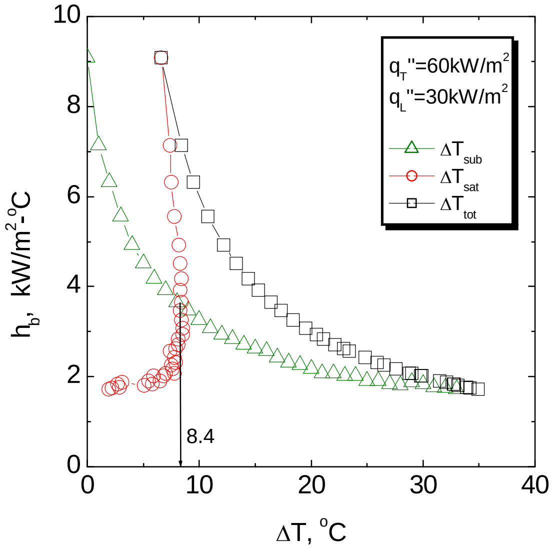

Fig. 5. Relation between h_b and ΔT .

The variations of the transition temperature and the heat transfer coefficient at the transition point against q''_L are shown in Fig. 6. Both $\Delta T_{transition}$ and h_b is increasing as q''_T increases. The transition temperature is also changed by q''_L . As the heat flux of the lower tube is increased the transition temperature is decreased at first. Then, $\Delta T_{transition}$ is slightly increasing at q''_L =90kW/m^2. The heat transfer coefficient at the transition temperature is increasing as q''_L increases. However h_b is increasing as q''_L varies from 60 to 90kW/m^2. The changes of $\Delta T_{transition}$ and h_b are clearly observed at q''_T =30kW/m^2 where the heat transfer is affected strongly by the bulk movement of bubbles and liquid coming from the lower side.

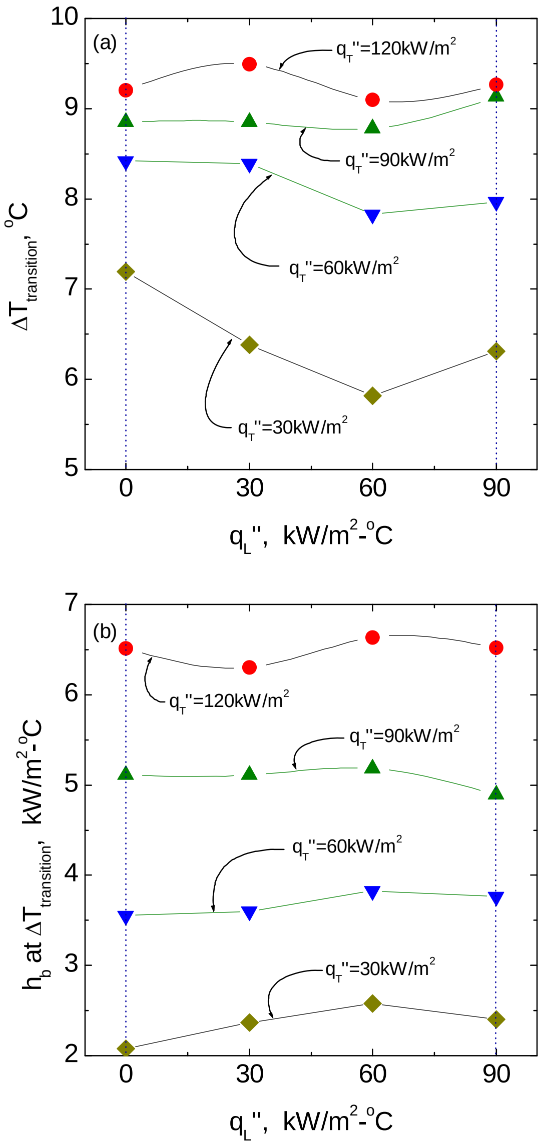

Fig. 6. Plots of $\Delta T_{transition}$ and h_b against q''_L .

To predict the transition temperature, an empirical correlation has been suggested by using the leastsquares method and experimental data gained from the present experiments. The empirical correlation can be correlated as a function of the heat fluxes as follows:

$$\Delta T_{transition} = -0.05q''_L + 10.23e^{0.0044q''_L - 11.35/q''_T} \qquad (2)$$

In the above equations, the dimension for q''_L and q''_T is kW/m². The unit for $\Delta T_{transition}$ is °C. The correlation only applies for the testing pressure and parameters.

To confirm the validity of the correlation the statistical analyses on the ratios of the measured and the calculated transition temperatures have been performed. The mean and the standard deviation are 1.00 and 0.03, respectively. A comparison between the measured transition temperatures and the calculated values by Eq. (2) is shown in Fig. 7. The newly developed correlation predicts the present experimental data within ±5 %.

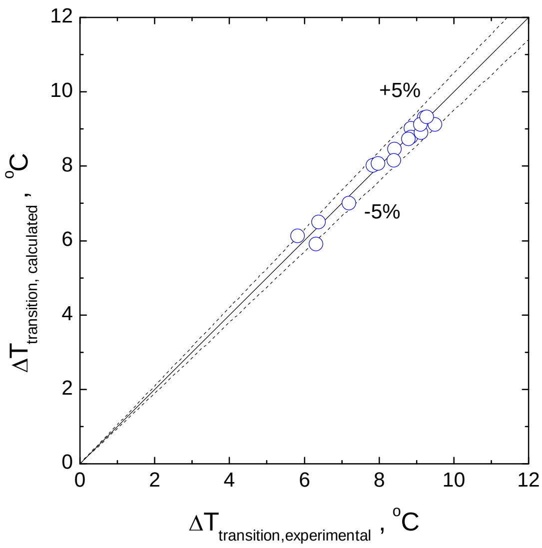

Fig. 7. Comparison of experimental data to calculated transition temperatures.

4. Conclusions

An experimental parametric study of a tube bundle with a 6° included angle has been carried out to determine the transition temperature in subcooled pool boiling of water under atmospheric pressure. The bundle consists of two stainless steel tubes of 19 mm outside diameter. Through the study following conclusions can be obtained:

(1) The transition temperature is changed by both heat fluxes on the lower and upper tube surfaces. The variation of the transition temperature due to the heat flux of the lower tube is clearly observed when the upper tube has a low heat.
(2) A new correlation was suggested to quantify the effects of heat fluxes on the transition temperature. The newly developed correlation predicts the experimental data within ±5 %.
(3) The results could be applied to the thermal design of passive safety features adopted in the advanced nuclear reactors.

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