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Experimental Study on the Thermal Stratification in a Pool Boiling with a Horizontal Heat Source

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1. Introduction

Thermal stratification is formed in horizontal fluid layers with different temperatures, where the warmer fluid layers are situated above the cooler fluid layers. Thermal stratification phenomena are common in pool type reactor systems, such as the liquid-salt cooled advanced high temperature reactor (AHTR) and liquid-metal cooled fast reactor systems such as the sodium fast reactor (SFR). Thermal stratification is increasingly encountered in large pools that are being used as heat sinks in the new generation of advanced reactors. As examples, the passive auxiliary feedwater system (PAFS) is one of the advanced safety features adopted in the APR+ (Advanced Power Reactor Plus), which is intended to completely replace the conventional active auxiliary feedwater system. The small-scale pool test was conducted to investigate the thermal stratification phenomena that occurred during the heat-up of a water in a pool. Because turbulence and boiling models affect the natural convection significantly, it is important to obtain local information regarding the fluid velocity and void distribution to determine the relevant physical models. To understand the flow phenomena inside a pool, a non-intrusive technique is adopted to measure the flow velocity field. In this study, the 2D particle image velocimetry (PIV) measurement technique is used to determine the fluid velocity vector field of single- and/or two-phase natural convection flow and thermal stratification in a pool.

2. Experimental Conditions and Procedures

The test rig consists of a pool of water with a single heater rod and the PIV measurement system. The test section, which consists of a single heater rod inserted inside a pool, was designed to measure single- and/or two-phase natural convection flow phenomena. The size of the water pool has been limited for visualization experiment. In this study, the pool volume was also reduced to 1/910 the size of the PASCAL prototype (Yun, 2010). Because the height of the pool is relatively low compared to the PASCAL prototype, this experimental study was conducted to focus on the thermal stratification and the natural convection flow behavior. Figure 1 shows a schematic of the water tank. The length and width of the pool are 300 mm and 60 mm, respectively. The initial water level is 400 mm. The back plate, which is 15 mm thick, is made from polycarbonate. The 3-mm-thick transparent Pyrex glass on the front side allows the thermal hydraulic phenomena inside the test section to be visualized, and thus, the PIV technique can be applied. Pyrex glass is also used for the right side window to illuminate the laser light sheet. The horizontal heater rod is asymmetrically installed in the water tank, as shown in Fig. 1. The horizontal heater rod, which has a diameter of 3/4", is installed at a vertical position of h=85 mm. The length of the inserted heater rod is 160 mm. Excluding the 10-mm-long non-heating portion of the rod, the actual length of the heating portion is 150 mm. The left side and bottom of the pool are made from a stainless steel plate with a thickness of 20 mm. Five K-type thermocouples were inserted into the pool to monitor and record the fluid temperature of the natural convection flow during the PIV experiments, as shown in Fig. 1. Thermocouples were placed at a distance of about 2 mm from the center line in the direction of depth. For the case of TF-02, thermocouple was installed 2 mm away from the heater rod's surface. The maximum uncertainty of the thermocouple used in this study was determined to be ± 1.1 ℃ at the experimental conditions.

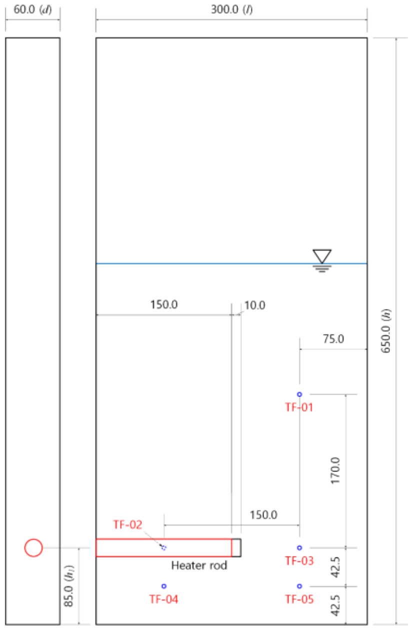


Fig. 1. Schematic of the pool (dimensions in mm).

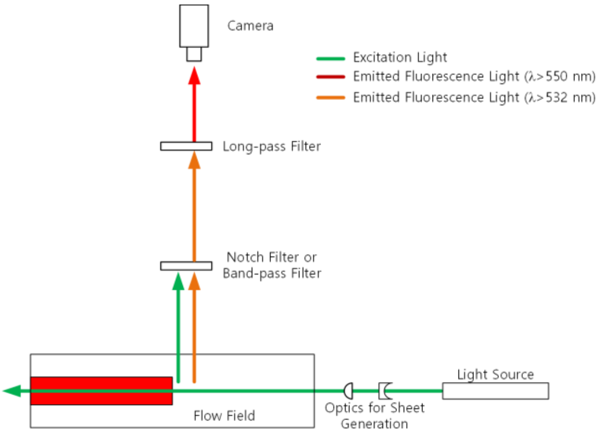


Fig. 2. Schematic of the experimental apparatus (top view).

Figure 2 shows a schematic diagram of the optical setup for PIV velocity field measurements, which consists of a 65-mJ Nd:YAG laser with an emission wavelength of 532 nm, a 2K×2K CCD camera and a pulse generator. The acquisition rate of the raw image is controlled by a pulse generator, and in this study, 8 frames per second is used. The laser light sheet illuminated the test flow through the right side (Pyrex glass) gap, as shown in Figure 4. De-ionized water was used as the working fluid for the PIV measurements. Fluorescent (Rhodamine B) polymer beads with an average diameter of 20 μm and a specific gravity of 1.02 were used as the tracer particles. A long pass filter (λ>550 nm) and a notch filter were used to eliminate the scattered light, except the fluorescence light, and block the 532-nm wavelength light, which were installed in front of the 2K×2K CCD camera. Using the ensemble average of 400 instantaneous velocity vector fields, statistical results were obtained, such as the mean velocity vector fields and turbulence intensity.

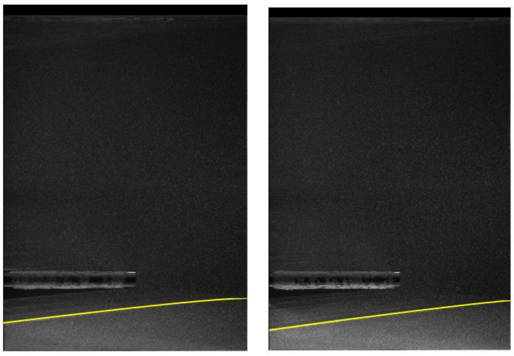
The small-scale pool test used to investigate natural convection flow and thermal stratification was performed at a test condition that corresponds to the maximum heat removal requirement of the PASCAL. Because it is required for a single rod of the PASCAL to remove 540 kW as its maximum heat removal rate, the test condition was determined according to the scaling ratio of the facility. Therefore, 600 W of thermal power was supplied to the electrical heater as the rated power. The overall experimental procedures were as follows. The electrical heater heated the test fluid until the fluid temperature reached the saturation temperature. Natural convection flow then formed inside the test section, and the speed of circulation flow increased as the pool temperature increased. Here, the pool temperature meant the average temperature from TF-01 to TF-03. PIV measurements were taken when the fluid temperature increased every 10 °C from the pool temperature, which was at 60 °C. Table 1 shows the experiment matrix and the order of this study. Five experimental cases were performed according to the temperature of the pool.

Table 1: Experiment matrix and order

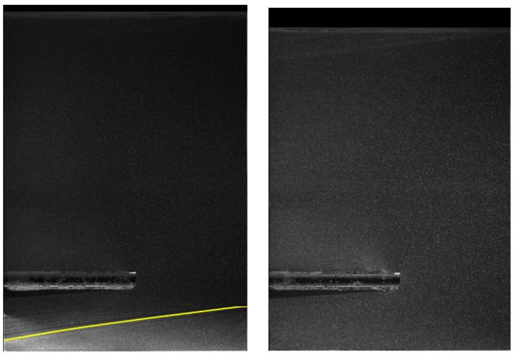
Experiment I.D.	Pool temperature (°C)	Pool height (mm)
T060H400	60	400
T070H400	70	
T080H400	80	
T090H400	90	
T100H400	100	

3. Results and Discussions

The PIV measurement technique was used to measure the complete fluid velocity fields in the pool under various fluid temperatures. Based on the scale ratio, 600 W of electrical power was supplied to the heater rod as the rated power. The fluid temperature above the heater rod increased over time. The heat transfer from the heater rod increased the pool temperature up to the saturation condition. Figure 3 shows the raw particle images for the case of T070H400 (T=72.0 °C) and with different water temperatures, which ranged from 72.0 to 98.1 °C. The collapsed water level increased until the pool temperature reached the saturation temperature due to volume expansion.



(a) T070H400 (b) T080H400



(c) T090H400 (d) T100H400

Fig. 3. Thermal boundary layer (yellow line) of the experimental cases.

The yellow line shows the thermal boundary layer of the stagnant region by the thermal stratification below the heater rod, as shown in Fig. 3(a)-3(c). In the lower region of the heater rod, the thermal boundary layer was thinner than in the opposite side of the heater rod due to the conduction heat transfer between the heater rod installed asymmetrically and the thermal boundary layer. The thickness of the thermal boundary layer was gradually reduced as a function of time.

Figure 4 show the enlarged horizontal mean velocity profiles in the lower region of the heart rod. As shown in Fig. 4, a flow which had higher temperature than that inside the thermal boundary layer flowed to the right direction. On the other hand, flow to the left direction caused by the convection flow of the upper region of the heater rod was shown in the opposite side of the heater rod. The region below the heater rod was considered the stagnant region by thermal stratification, but a flow in the opposite direction to each other actually existed in the upper region of the thermal boundary layer, as shown in Fig. 4. The water temperature of the flow flowing to the right direction is relatively lower than that of the flow flowing to the left direction. The flow flowing to the right side is located below the flow flowing to the left side. Even though the speed of flow just above the thermal boundary layer was much smaller than that of the flow flowing to the left direction and it is almost close to zero. From the present experimental result, it could be concluded that this flow pattern contributed to maintain the thermal stratification and retard the water temperature rise at the lower region of the heater rod by preventing a flow which flowed to the opposite direction to penetrate into the stagnant region. The flow of the opposite direction to each other was disappeared when the water temperature was reached to the saturation temperature and the thermal stratification was also dissipated.

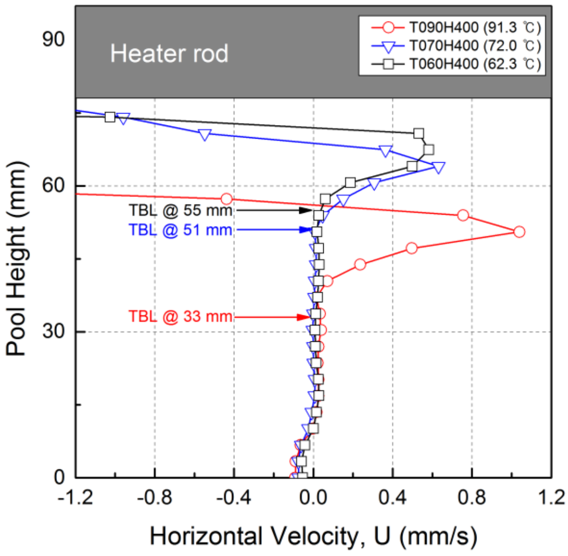


Fig. 4. Enlarged horizontal mean velocity profiles with different pool temperatures at *l*=150 mm.

4. Conclusions

Detailed velocity measurements using the 2D PIV measurement technique were conducted to investigate single- and/or two-phase natural convection flow and thermal stratification in a pool boiling. In this study, the two-dimensional velocity vector fields as the water temperature increased were experimentally acquired in a pool that contained a horizontal heater rod. The experimental results indicate a large natural convection flow at the region above the heater rod and thermal stratification at the region below the heater rod. The flow of the opposite direction to each other was shown in the region between the heater rod and the thermal boundary layer. This flow pattern will contribute to maintain the thermal stratification and retard the water temperature rise and the dissipation of the thermal stratification at the stagnant region in a pool boiling with a horizontal heat source installed asymmetrically. The thermal stratification and stagnant region began to disappear when the pool temperature reached to over 90 °C. Because the present experiment identified local multi-dimensional parameters, such as the turbulence intensity and turbulent kinetic energy, which are essential parameters in CFD analysis, the current experimental data can be directly used to develop and validate turbulence models in a pool boiling. Furthermore, the present experimental results can help characterize the performance of boiling models on heated surfaces and provide benchmark data to validate the calculation performance of a thermal hydraulic system analysis code.

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