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Velocity and temperature fields measurement of natural circulation flow inside a pool using PIV and PLIF technique

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ABSTRACT

Thermal stratification is encountered in large pool of water increasingly being used as heat sink in new generation of advanced reactors. These large pools at near atmospheric pressure provide a heat sink for heat removal from the reactor or steam generator, and the containment by natural circulation as well as a source of water for core cooling. For examples, the PAFS (passive auxiliary feedwater system) 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 [1, 2]. The PAFS cools down the steam generator secondary side and eventually removes the decay heat from the reactor core by adopting a natural convection mechanism. In a pool, the heat transfer from the PCHX (passive condensation heat exchanger) contributed to increase the pool temperature up to the saturation condition and induce the natural circulation flow of the PCCT (passive condensate cooling tank) pool water [3]. When a heat rod is placed horizontally in a pool of water, the fluid adjacent to the heat rod gets heated up. In the process, its density reduces and by virtue of the buoyancy force, the fluid in this region moves up. After reaching the top free surface, the heated water moves towards the other side wall of the pool along the free surface. Since this heated water is cooling, it goes downward along the wall at the other side wall. Above heater rod, a natural circulation flow is formed. However, there is no flow below heater rod until pool water temperature increases to saturation temperature. In this study, velocity measurement was conducted to reveal a natural circulation flow structure in a small pool using PIV (particle image velocimetry) measurement technique.

1. INTRODUCTION

Thermal stratification is formation of horizontal layers of fluid of varying temperature with the warmer layers of fluid placed above the cooler ones. Thermal stratification is encountered in large pool of water increasingly being used as heat sink in new generation of advanced reactors. These large pools at near atmospheric pressure provide a heat sink for heat removal from the reactor or steam generator, and the containment by natural circulation as well as a source of water for core cooling. For examples, the PAFS (Passive Auxiliary Feedwater System) 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 (Song, 2010 and Cheon, 2010). It is composed of a steam-supply line, a passive condensation heat exchanger (PCHX), a return-water line, and a PCCT (Passive Condensate Cooling Tank). The PAFS cools down the steam generator secondary side and eventually removes the decay heat from the reactor core by adopting a natural convection mechanism. In a pool, the heat transfer from the PCHX contributed to increase the pool temperature up to the saturation condition and induce the natural circulation flow of the PCCT pool water. When a heat rod is placed horizontally in a pool of water, the fluid adjacent to the heat rod gets heated up. In the process, its density reduces and by virtue of the buoyancy force, the fluid in this region moves up. After reaching the top free surface, the heated water moves towards the other side wall of the pool along the free surface. Since this heated water is cooling, it goes downward along the wall at the other side wall. Above heater rod, a natural circulation flow is formed. However, there is no flow below heater rod until pool temperature increases to saturation temperature.

In the present study, a small scale pool test rig with a single heater rod simulates the PAFS prototype. The volume of pool was also reduced to 1/910 of the PASCAL (PAFS Condensing heat removal Assessment Loop) prototype. In order to understand the flow phenomena inside a pool, it is reasonable that non-invasive technique is adopted to measure the flow velocity field and temperature field. In this study, the 2D PIV and LIF measurement technique is adopted to get velocity vector field and temperature distribution of a natural circulation flow and thermal stratification in a pool. The CFD-grade experimental results will contribute to provide the benchmark data for validating the calculation of thermal hydraulic phenomena inside a pool with a heat source.

2. EXPERIMENTS

2.1 Experimental Apparatus

The test section by inserting a single heater rod inside a pool was designed for measurement of natural circulation flow phenomena. Since it is required for a single train of the PAFS to remove 129.8 MW as a maximum heat removal rate by 240 tubes of the PCHX, 540 kW of thermal power was supplied to generate a steam flow into the single tube of the PASCAL facility according to the scaling ratio of the facility (1/240). Therefore, the condensation heat exchanger for PASCAL facility has a heat removal capacity of 540 kW as a nominal heat removal capacity. In this study, the volume of pool was also reduced to 1/910 of the PASCAL prototype (Yun, 2010). Major design and scaling parameters of the test section are compared with those of the PASCAL prototype in Table 1. In order to preserve the internal volume of a pool, dimension of the test section was scaled by volume ratio. The length and the width of the pool are 300 mm and 60 mm, respectively. And the height of the pool is 400 mm. The test rig consists of a water pool with a single heater rod, a constant temperature bath. The test section is made by transparent windows and 3/4" diameter of a heater rod is installed at h=90 mm vertical position. The thermal capacity of a heater rod is about 2 kW. An overall description of the experimental apparatus is illustrated in Fig. 1. The test section to be observed in the direction of the front transparently made of polycarbonate. So take advantage of PIV and LIF techniques are possible. The test section has six k-type thermocouples installed inside a pool for measuring the temperature of the natural circulation flow. The maximum uncertainty of the thermocouple was expected to be 1.1 °C at the operation condition.

Table 1 Geometry and scaling parameters of test section and PASCAL facility

Parameter	PASCAL	Model	Scale ratio
h (m)	8.9	0.4	22:1
l (m)	6.7	0.3	22:1
d (m)	0.112	0.06	1.87:1
h1 (m)	2	0.09	h/h1, 1:1
Power (kW)	540	0.6	910:1

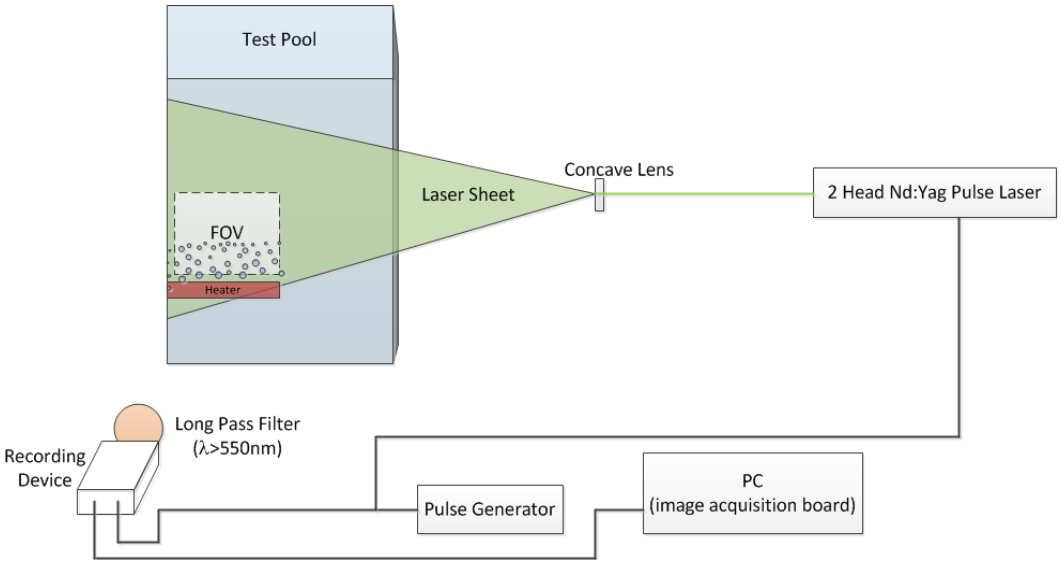


Figure 1 Schematic of the experimental apparatus

2.2 PIV Measurement Technique

Particle image velocimetry (PIV) is an optical method of flow visualization. It is used to obtain instantaneous velocity measurements and related properties in fluids. The fluid is seeded with tracer particles which, for sufficiently small particles, are assumed to faithfully follow the flow dynamics. The fluid with entrained particles is illuminated by laser light sheet so that particles are visible. The motion of the seeding particles is used to calculate the velocity field of the flow being studied. Other techniques used to measure flows are Laser Doppler velocimetry and Hot-wire anemometry. The main difference between PIV and those techniques is that PIV produces two dimensional or even three dimensional vector fields, while the other techniques measure the velocity at a point. During PIV, the particle concentration is such that it is possible to identify individual particles in an image, but not with certainty to track it between images. Typical PIV apparatus consists of a recording device, a laser with an optical arrangement to limit the physical region illuminated, a synchronizer to act as an external trigger for control of the camera and laser, the seeding particles and the fluid under investigation (Westerweel, 1993).

The small scale pool test was performed investigate the thermal mixing characteristics locally. Because the turbulence and boiling models affect the natural convection significantly, it is important to know the local information of fluid velocity and void distribution to determine the relevant physical models. In this study, the two-dimensional PIV measurement technique is used to measure the velocity vector field. Fig. 3 shows the small pool test. Figure 1 shows the schematic diagram of experimental setup for PIV velocity field measurements. It consists of 150 mJ Nd:YAG laser with an injection seeder, 2K×2K CCD camera and a pulse generator. The laser light sheet illuminated the test flow through the right side polycarbonate acryl side gap as shown in figure 1. Working fluid used for PIV measurements was de-ionized water. Fluorescent polymer beads of about 8 μm in mean diameter were used as tracer particles. A long pass filter (λ>550 nm) is used to eliminate the scattered light except the fluorescence light, and it is installed in front of a digital recording device.

2.3 LIF Measurement Technique

Various techniques have been used previously to obtain the spatial distribution of the temperature in water. Thermo-chromic liquid crystals (TLC) are commonly used to visualize temperature qualitatively. It is now possible to obtain quite sensitive TLC particles which change color from red to blue in a range of 1 K or less. However, the accuracy relative to the measurement range is not still large. The uncertainty is approximately 0.1 K, with an available measurement range of 0.7 K. Instead of using TLC particles, temperature-sensitive fluorescent dyes excited by laser light can alternatively be used as a molecular marker representing temperature of solution of the dyes. Instead of using TLC particles, laser-induced fluorescence (LIF) which uses temperature sensitive fluorescent dyes excited by laser light can alternatively be used as a molecular marker representing temperature of solution of the dyes. An advantage of LIF against liquid crystals is the better accuracy relative to the temperature range which is typically 1.5 °C for a 40 °C temperature range. LIF is based on natural fluorescence of molecules and atoms which is induced by absorption of a photon (energy). This absorption causes a transition from the ground state to an excited state. Part of the absorbed energy is re-emitted during spontaneous transition from the excited state to the ground state (fluorescence).

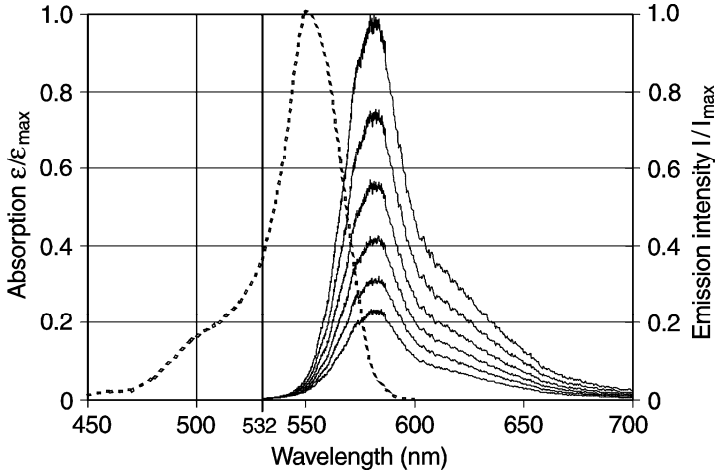


Figure 2 Absorption and emission spectra of rhodamine B for different fluid temperature (Coolen, 1999)

Fluorescence intensity is decreased by 2-3% per Kelvin. The decrease of fluorescence intensity for increasing temperatures is caused by a decrease in quantum yield. This decrease is not wavelength dependent as can be concluded from the fluorescence spectra shown in Fig. 2 which are obtained by using an Ar-ion laser (Coolen, 1999). As one can see a higher temperature results in an overall decrease of the emission spectrum. This feature combined with the fact that fluorescence occurs at a longer wavelength than absorption makes it possible to separate the fluorescence signal from elastically scattered laser light (without energy loss). This is achieved by placing a long-wave pass filter in front of the camera lens which blocks light with a wavelength smaller than 550 nm almost completely as shown Fig. 1. The absorption spectrum maximum of rhodamine B dissolved in water is near 550 nm. From this figure it can be concluded that the Nd :YAG laser is suitable for excitation. Besides, the excitation wavelength of this Nd :YAG laser (532 nm) is closer to the absorption maximum than the excitation wavelength of an Ar-ion laser (514.5 nm). This means that for an equal excitation intensity a Nd :YAG laser will result in a higher fluorescence intensity. In this work the fluorescent dye rhodamine B (MW=379.02) is dissolved in demineralized water with a concentration of 6 mg per liter. In order to measure temperatures, a calibration curve between temperature and fluorescence intensity is necessary. To obtain calibration curve, the temperature dependence of the fluorescence intensity is measured by heating the test fluid to uniform temperatures. The uniform temperatures are achieved by constant temperature bath. The temperature dependence is measured in the middle of the test section in 6 measurement points.

2.4 Experimental Conditions and Procedures

The small scale pool test for investigation of natural circulation flow and thermal stratification was performed according to the maximum heat removal requirement of the PASCAL. Since it is required for a single rod of the PASCAL to remove 540 kW as a maximum heat removal rate, the test condition was determined according to the scaling ratio of the facility as indicated in the Section 2.1. Therefore, 600 W of thermal power was supplied in the electrical heater as a rated power. Overall procedures for the experiment are listed as follow. The electrical heater heated up the test fluid until the fluid temperature reached 60 °C. The natural circulation flow was already formed inside the test section. PIV or LIF measurement was performed when the fluid temperature increased every 10°C. The fluid temperature from 6 thermocouples was also measured.

3. RESULTS AND DISCUSSION

3.1 PIV Results

According to the scale ratio, 600 W of thermal power was supplied at electrical heater rod as a rated power. The temperature above the heater rod was increased by the larger heat flux. The heat transfer from the heater rod contributed to increase the pool temperature up to the saturation condition and induce the natural circulation flow of the pool.

Figure 3 showed raw particle images with different pool temperature. Collapsed water level was increased until pool temperature reached to saturation temperature. Void fraction is also increased by decreasing collapsed water level.

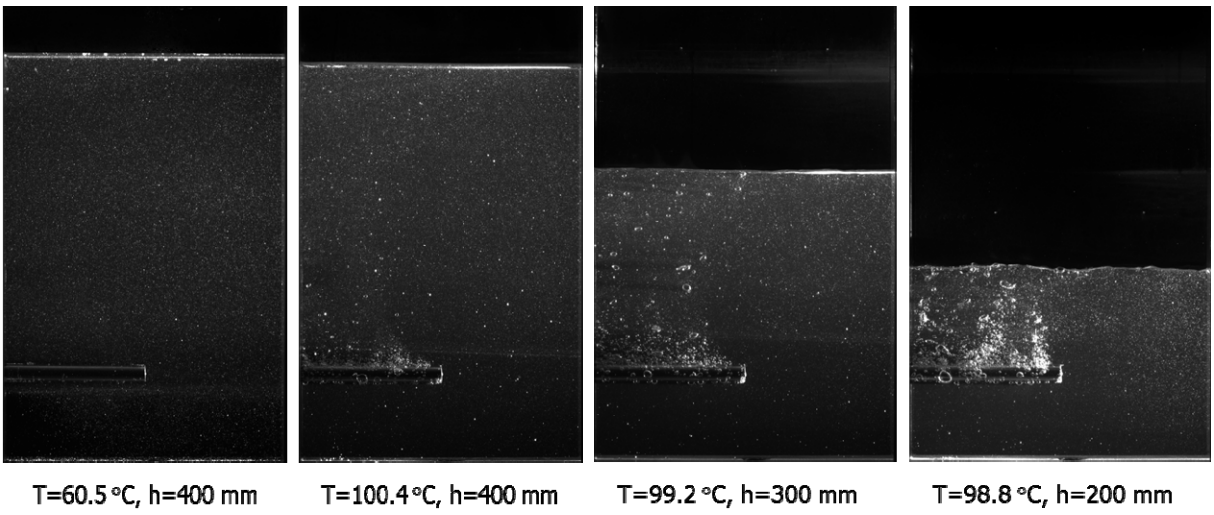


Figure 3 Raw particle images with different pool temperature

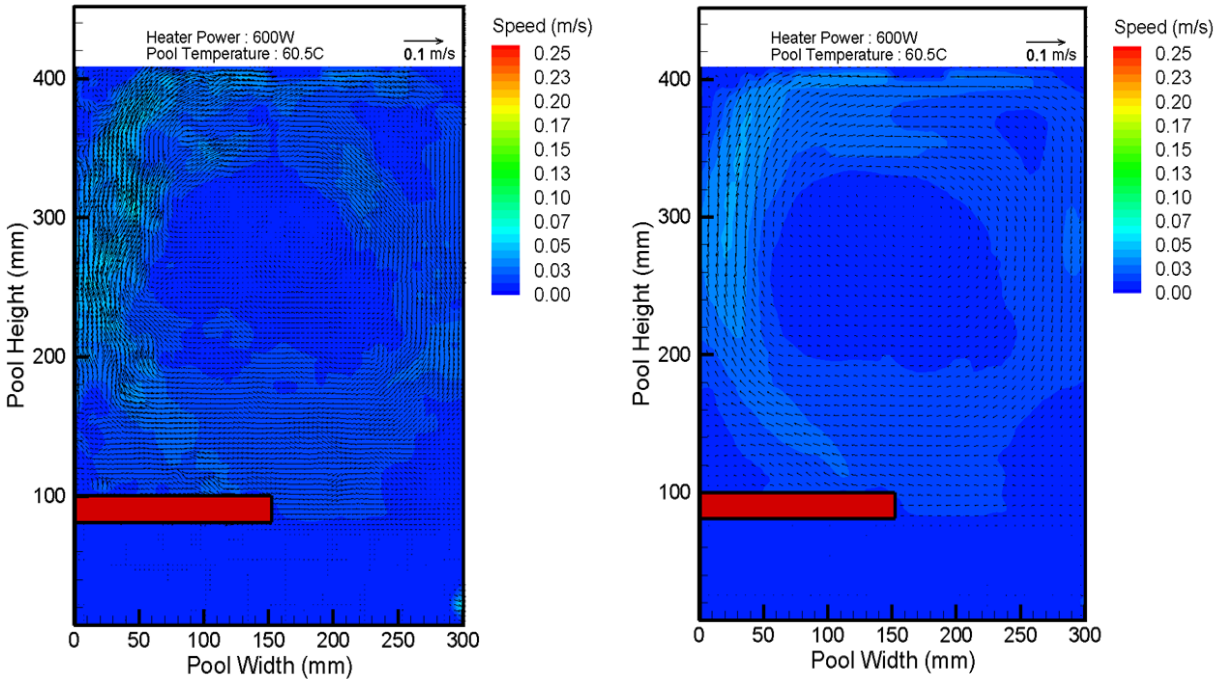


Figure 4 Instantaneous and mean velocity vector field (Pool temperature is 60.5 °C)

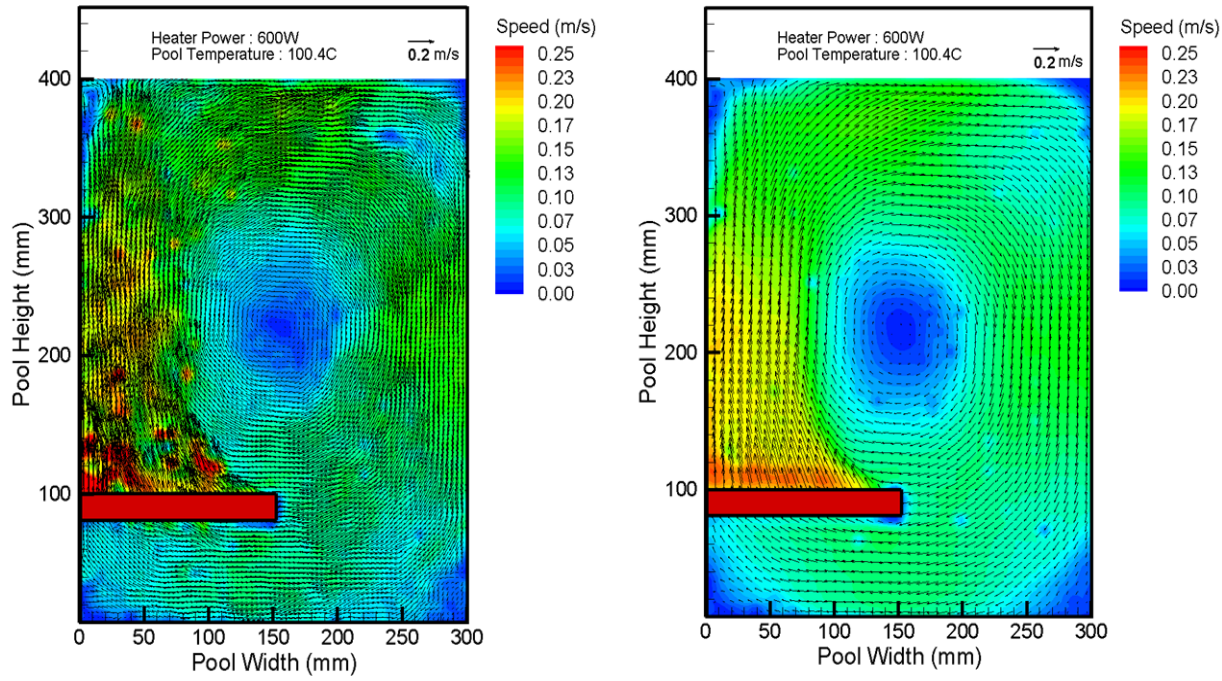


Figure 5 Instantaneous and mean velocity vector field (Pool temperature is 100.4 °C)

Figure 4 showed instantaneous and mean velocity vector field at pool temperature 60.5 °C and pool water level 410 mm. By increasing pool temperature, pool water level was also increased. At this time, a circulation flow was already formed. However, there was no flow below a heater rod. Break-up of thermal stratification started when the pool temperature was saturation temperature as shown in Fig. 5. Figure 5 showed instantaneous and mean velocity vector filed at pool water level 400 mm. After pool boiling occurred, pool water level was decreased continuously. A natural circulation flow speed above/below a heater rod was increased continuously.

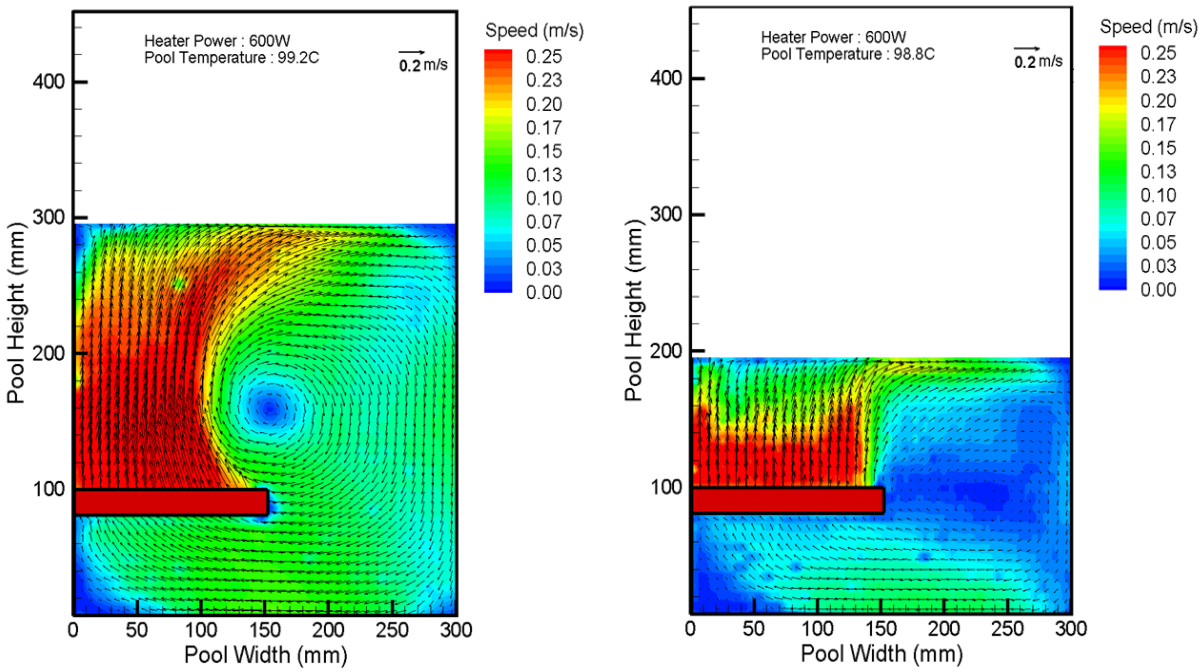


Figure 6 Mean velocity vector field with different collapsed water level

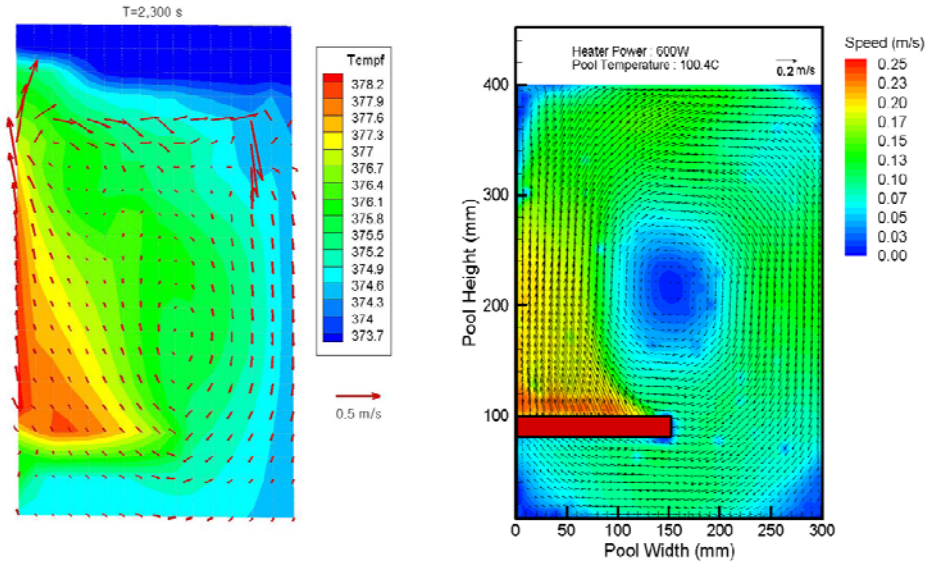


Figure 7 Comparison with MARS-KS result

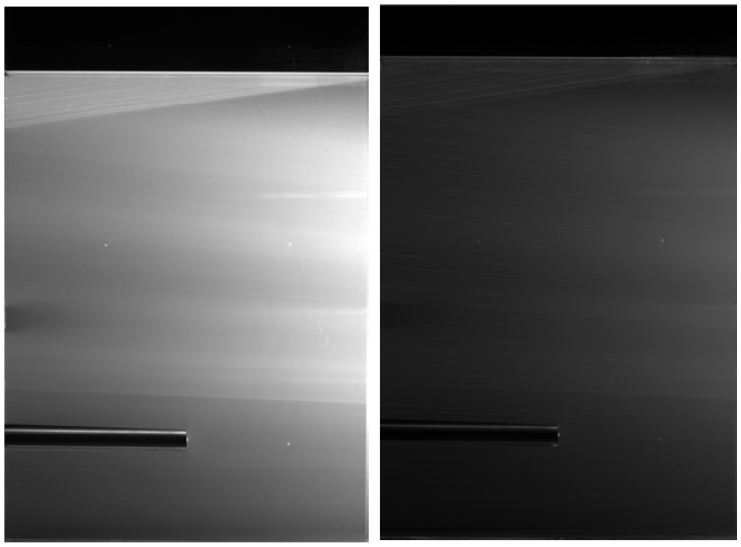
Figure 6 showed mean velocity fields with different collapsed water level. Due to boiling inside a pool, collapsed water level is decrease continuously. Above the electrical heater rod, void fraction was increased by decreasing collapsed water level. In case of the collapsed water level 300 mm, natural circulation flow strength below the electrical heater rod was larger than that of collapsed water level 400 mm. For the case of the collapsed water level 200 mm, natural circulation flow pattern was disappeared and mixed flow pattern was showed.

A thermal hydraulic system analysis code, MARS-KS (Multi-dimensional Analysis for Reactor Safety, KINS Standard Version), was utilized to validate the present experimental data. Figure 7 showed the comparison MARS-KS (Multi-dimensional Analysis for Reactor Safety, KINS Standard Version) code results with PIV velocity vector field. The calculation result of the MARS-KS code presented the natural circulation flow pattern with a good agreement. The

present experimental results will contribute to improve the model of the turbulence and boiling models, and also to provide the benchmark data for validating the calculation performance of a thermal hydraulic system analysis code.

3.2 LIF Results

LIF calibration images were shown in Fig. 8. During calibration experiment, LIF intensity was decreased continuously with increasing pool temperature. Figure 9 showed LIF raw excitation intensity image for the case of pool temperature, T=60.3 °C and T=97.1 °C. From Fig. 9, a hot plume was rising from the electrical heater rod, and thermal stratification was formed below electrical heater rod for the case of T=60.3 °C. At that time, a pool temperature below the electrical heater rod is 5~10 °C lower than that of upper region. Instantaneous temperature distribution of pool temperature T=60.3 °C and T=97.1 °C were shown in Fig. 10. Due to pool boiling, the thermal stratification region was broken-up and pool temperature was increasing when the natural circulation flow is introduced into the lower region.



T=52 °C T=99 °C

Figure 8 LIF calibration image with different pool temperature

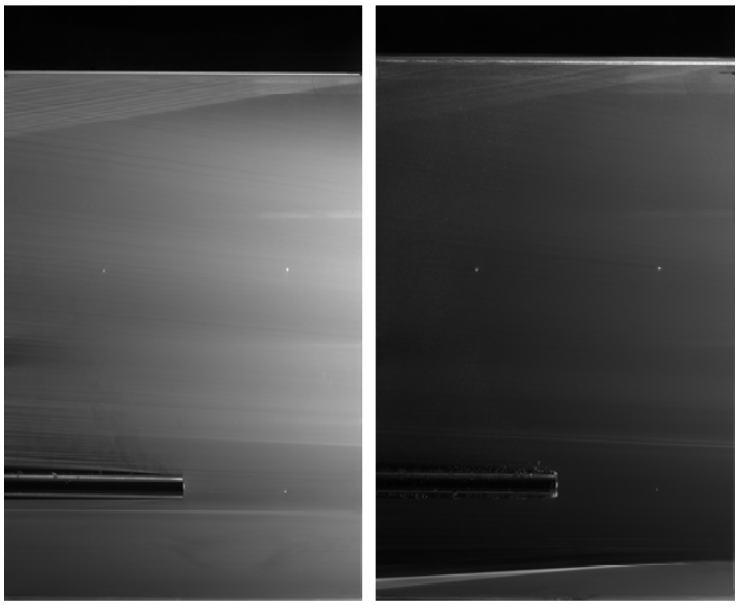


Figure 9 LIF excitation intensity image

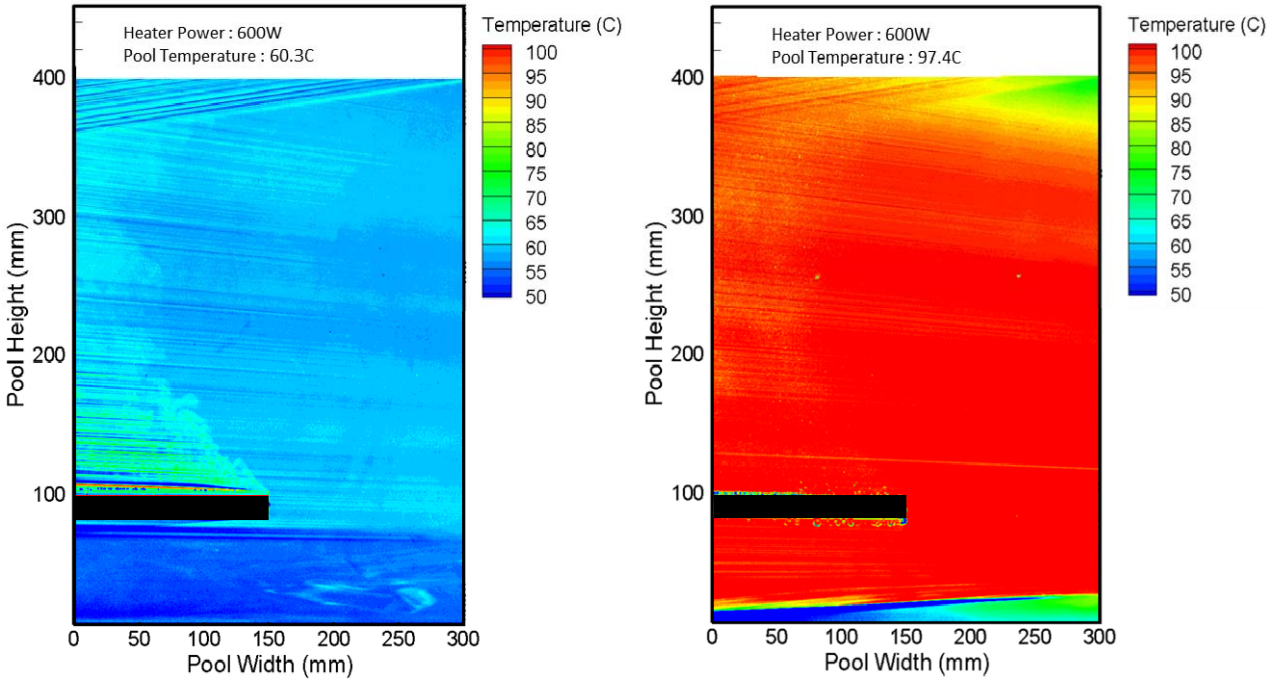


Figure 10 Instantaneous temperature distribution with different pool temperature

4. CONCLUSION

Detailed velocity and temperature measurements using 2-D PIV and LIF measurement technique have been conducted on the subject of the natural circulation flow and thermal stratification inside a small scale pool. In this study, two-dimensional temperature distribution and velocity vector fields during the decrease of water level was experimentally investigated in a pool which has a horizontal heater rod. Experimental results show a large natural circulation flow above a heater rod and thermal stratification below a heater rod. Thermal stratification and no flow region start to break up when pool temperature is saturation temperature. The CFD-grade experimental results will contribute to provide the benchmark data for validating the calculation of thermal hydraulic phenomena inside a pool with a heat source.

ACKNOWLEDGMENTS

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