13th International Symposium on Particle Image Velocimetry – ISPIV 2019
Munich, Germany, July 22-24, 2019

PIV/LIF measurements of the natural convection flows

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Abstract

The velocity and temperature fields of natural convective flows are investigated using particle image velocimetry and laser-induced fluorescence. A Large-scale circulation (LSC) and a thermal plume are observed by the mean flow fields. The initial developing height of the vortex flows in a confined space corresponds to that of the LSC center in a broad space. The local Richardson number indicate that shear and inertia play similar roles to that of buoyancy, except for the mean flow near the heater in a confined space. The regions of significant energy transfer due to shear and heat are near the free surface and middle layer, respectively. In order to investigate the energy transfer between the mean flow and turbulence, the turbulent energy production is calculated. The turbulent energy production show that dissipated energy from the thermal plume to the turbulence causes the LSC and vortex flows.

1 Introduction

Natural convection is a flow occurring due to the density difference caused by a temperature gradient or heterogeneous multiphase flow. Thermal natural convective flows occurs in a water pool of a passive safety system which has been received large attention in nuclear power systems after the Fukushima accident (Choi et al. 2013, Kim et al. 2017, and Park et al. 2017). Spatial distributions of velocity and temperature are required for the design and safety analysis.
Quantitative measurements of the velocity and temperature are essential for understanding the behaviors of thermal convective flows. With advances in laser and digital image-processing techniques, particle image velocimetry (PIV) has been accepted as a reliable method for obtaining the velocity field information of various flows (Adrian 1991). PIV has recently been applied to obtain velocity-field information in the case of natural convection (Gandhi et al. 2011, Grafsrønningen et al. 2011, and Kim et al. 2017). Laser-induced fluorescence (LIF) is one of the most common techniques for measuring quantitative temperature field information (Coppeta and Rogers 1998, and Hsieh et al. 2017). Fluorescence, which is a re-emission of the absorbed energy, occurs during a transition from an excited state to a lower energy state. The fluorescent intensity depends on the quantum efficiency with a change of the temperature.
In the present study, the velocity and temperature fields of natural convective flows are measured using the PIV and LIF techniques. The mean and fluctuated information of the velocity and temperature are examined. In order to understand the dynamics of energy transfer and turbulence, the turbulent energy production P, local Richardson number (Ri) are calculated.

2 Experimental apparatus

Figure 1 shows a schematic diagram of the experimental setup. A test chamber is designed for simulating a pool in a simple passive safety system. The test rig consists of a water pool with a horizontally inserted heater rod. The thickness and width are 0.060 and 0.300 m, respectively. The diameter (D) of the heater rod is 0.0127 m. The total length of the heater is 0.200 m, but only a 0.150-m-long portion is located inside the water pool. The height from the bottom to the heater center is 0.085 m, and the water pool level is 0.200 m. The test chamber is made of transparent acryl with a thickness of 0.010 m for illumination and image acquisition. The power of the heater is 600 W, and the corresponding heat flux (q''_0) from the heater surface is 0.0752 W/mm^2.

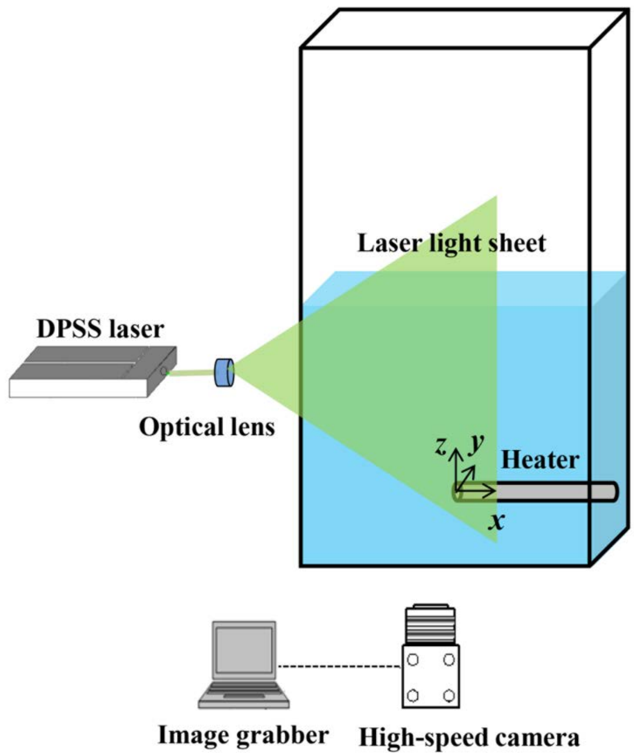

Figure 1: Schematic of the experimental apparatus

A high-speed camera was employed and the camera was positioned in front of and on the side of the test rig to capture images for obtaining the temperature and velocity field information on two planes. A thin light sheet was formed by using an 8-W diode-pumped solid-state continuous laser (a wavelength of 532 nm) with optical lens. Silver-coated hollow glass particles having a diameter of 44 μm were seeded as tracer particles for the PIV measurements. Particle images were consecutively recorded at 250 frames per second (fps), and the physical sizes of pixels for the front and side views were 0.752 and 0.208 mm, respectively. The images were processed using an open-source software for performing PIV analysis in MATLAB (Thielicke et al. 2014).

For the LIF measurements, the same laser was used in the PIV measurements. Rhodamine B was used as a temperature-sensitive fluorescent dye which has larger emission spectrum than the incident wavelength and a maximum at about 575 nm for the 532 nm incident light (Seuntiëns et al.

2001). A red color filter was positioned in front of the camera lens to get only the emitted intensity. Images for LIF measurements were recorded at 50 fps.

In order to obtain temperature information from the fluorescence intensity, the relationship between the fluorescence intensity and temperature should be known. Therefore, the relationship was obtained with a calibration process. Although the fluorescence intensity depends on the concentration, incident intensity, and experimental conditions, it is known that the relationship between the normalized fluorescence intensity and the temperature is independent with these factors (Coolen et al. 1999 and Seuntiëns et al. 2001). Figure 2 shows the calibration curve between the normalized fluorescence intensity and the temperature. In the temperature calculation in experiments, the inverse relation of this curve was used.

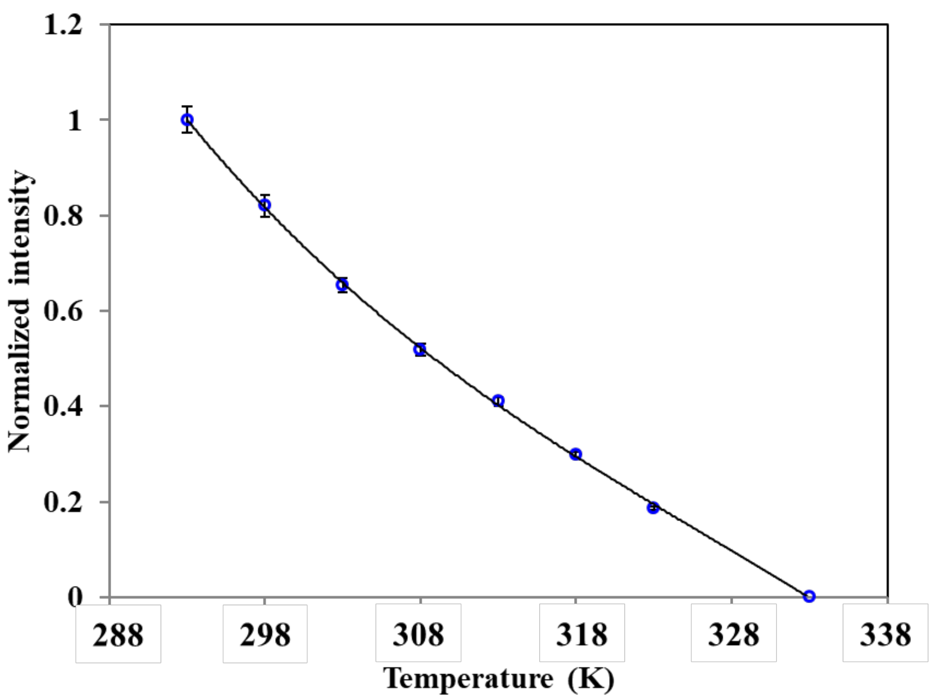

Figure 2: Calibration curve between the normalized fluorescence intensity and the temperature

3 Results

Figure 3 shows mean velocity vectors and temperature contours. Large scale circulation (LSC) which is a distinct structure in a natural convection is observed in a front view. Rising plume occurs on the heater rod due to temperature gradient, and water flows horizontally near the free surface. Thereafter, it goes down and returns to the heater. Since hot water goes upward at the heater side and cold water goes down in the opposite side, thermal stratification is formed. In a side view, the rising plume initially has similar shape with a jet near a heater. As it goes up, it dissipates to lateral directions and vortex flows occur at both sides near a free surface.

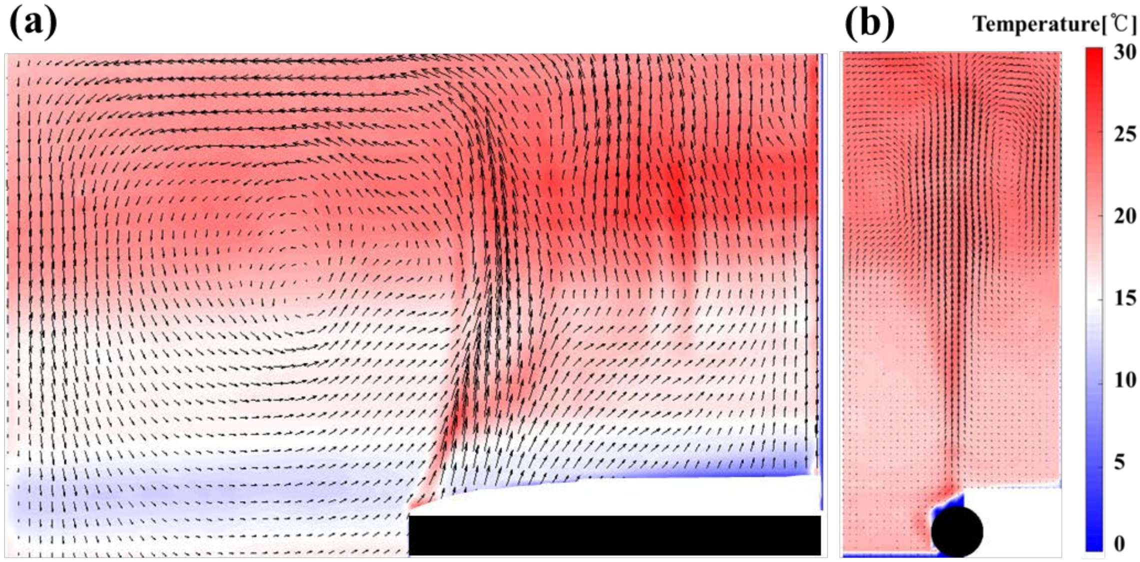

Figure 3: Mean velocity vectors and temperature contour in (a) a front view and (b) a side view

Both the buoyancy and the inertia are dominant in this flow. In order to investigate the dominant effects, the local Ri was obtained as follows:

$$\mathrm{Ri}_D = \frac{g\beta\Delta T}{V^2} D, \quad (1)$$

where V is the average velocity magnitude and ΔT is the average temperature difference. Figure 4 shows variations of Ri. In the front view, Ri initially decreased and then increased as z increases. It has a peak near the LSC center and then decreases as flows approach the free surface. Most of the Ri values were close to 1 in the front view. This means that the inertia of LSC plays a similar role to the buoyancy flows although the initial flows are caused by the buoyancy. In the side view, with increase of z, Ri decreases and approaches 1. Where $z < 5D$, Ri is larger than 1 and the maximum Ri is 5.47 at the lowest position. This Ri variation indicates that buoyancy plays a significant role in flows in a confined space before beginning the dissipation of jet flows as shown in Fig. 3.

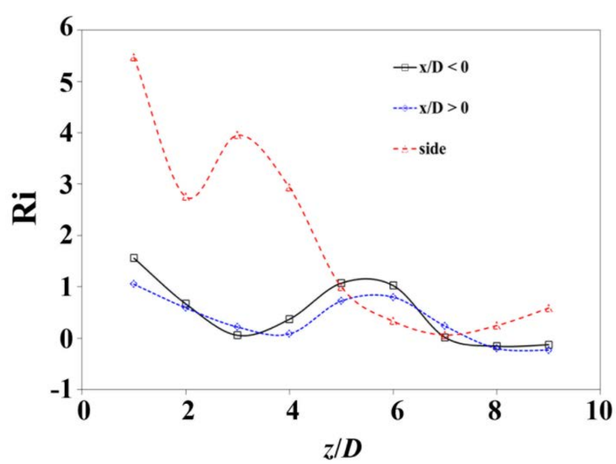

Figure 4: Richardson number with respect to the z position

To understand the energy transfers between the mean flows and turbulence, the production of the turbulent kinetic energy $P\left(-\overline{u_i'u_j'}\,\partial u_i/\partial x_j\right)$ was investigated from the mean and fluctuation velocity information. Figure 5 shows the contours of P. In general, a positive P represents the energy transfer from the mean flows to turbulence, whereas a negative P indicates that mean flows receive energy from turbulence. In the front view, the facing positive-negative P is observed along the vertically upward flow having high velocity in Fig. 3. This implies that, in addition to buoyancy, the mean flow was driven by fluctuations or Reynolds stress associated with the thermal plumes, and the energy of the vertical upward flow was simultaneously dissipated into the turbulence associated with the LSC. In a confined space (side view), the energy of the thermal plume was mainly transferred to turbulence where z is higher than $5D$. This energy transfer induced vortex flows.

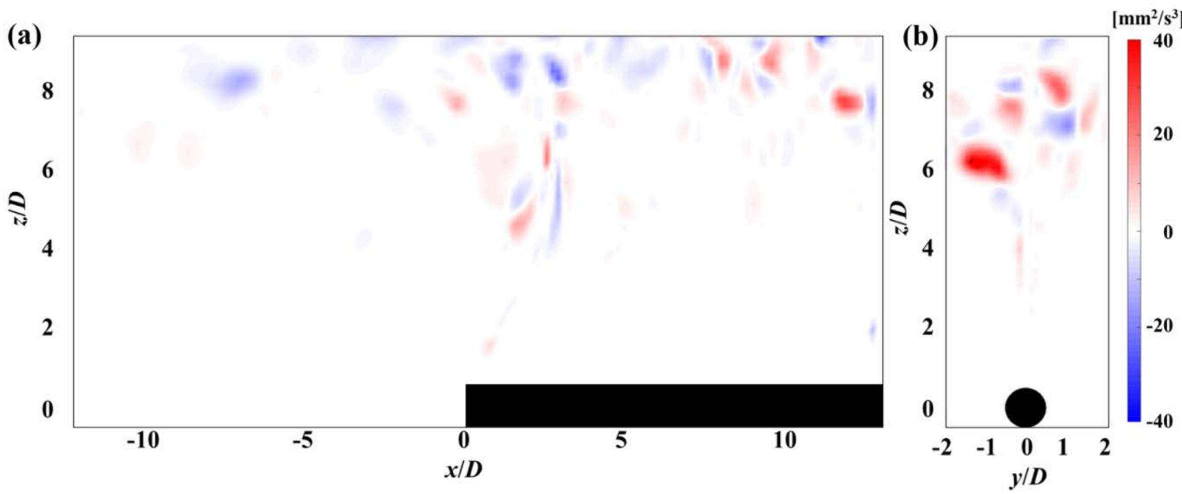

Figure 5: The production of turbulent kinetic energy P in (a) a front view and (b) a side view

4 Conclusion

The velocity and temperature fields of natural convective flows are investigated using PIV and LIF. The mean velocity in a broad space represents a typical natural convective flow having LSC and upward thermal plume. A jet-like buoyant plume flow is developed in a confined space, and vortex flows are generated with the dissipation of the jet flow. The Ri variation shows that the buoyancy played a significant role in flows near the heater for a confined space. Except for this region, shear and inertia played similar roles with the buoyancy caused by the heat transfer from the heater. The P distributions demonstrate that the energy dissipated from the thermal plume to the turbulence drives the LSC and vortex flows at the sides of the buoyancy plume.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (NRF-2017R1C1B5017479) and Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20174030201620).

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