Laser Induced Fluorescence and Particle Image Velocimetry for the investigation of large-scale structures in turbulent Rayleigh-Bénard convection with high aspect ratio

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ABSTRACT

We report about temperature und velocity field measurement in turbulent thermal convection. With LIF and PIV we measured large-scale flow pattern in a so-called Rayleigh-Bénard cell, a rectangular box heated from below and cooled from above. The cell with large aspect ratio was filled with water (LIF) and air (PIV). Temperature field measurements with planar LIF in water convection were carried on in a vertical plane, where the laser light sheet was perpendicular guided through a transparent cooling plate. For the planar PIV measurements in air the whole horizontal cross section of the convection cell was illuminated and the PIV images were taken from a camera below the convection cell through a transparent heating plate. Both temperature and velocity fields show large-scale structures. After time-averaging the turbulent velocity field coherent flow pattern became visible. Both instantaneous and time-averaged velocity field were in a good agreement with numerical simulations (DNS).

1. Introduction

Heat and mass transfer in natural convection are directly coupled and are accessible by measuring the temperature and velocity field of thermal convection [1]. Commonly the velocity field of thermal convection is measured by particle image velocimetry (PIV). Therefore particles are added to the fluid requiring similar density to prevent sedimentation of the particles and permit easy follow of the convective flow of mass [2]. Thus particle imaging velocimetry is a complementary measurement of thermal convection yielding just the velocity field of mass flow. On this ground, it is more reasonable to directly measure the temperature field, though it is experimentally harder to access. Different methods were applied to measure the thermal fields in fluids. For example laser induced fluorescence (LIF) [3,4], thermochromic liquid crystals (TLCs) [5,6] or thermochromic phosphor particles (TPPs) [7,8] were developed for measuring 2D temperature fields in laser light sheet illumination. Whilst TLCs have very narrow temperature scale of several Kelvin, but high resolution, LIF and TPP provide temperature range of several
decades to hundreds of Kelvin, which is important for studying turbulent flow at large temperature gradients. Since our study aims on investigation of turbulent flow at large aspect ratio in water, LIF is the most suitable method, simply to apply and analyze. Since the convective cell is mostly a closed system with given height, the only opportunity to change the Rayleigh number $Ra$ is the variation of temperature between heated and cooled enclosure from very low to very large gradients, requiring a temperature detecting technique spanning a possibly large temperature range. A further advantage of LIF is the diversity and excellent solubility of organic dyes [9] in various fluids and the direct response to temperature change as the single molecules are in direct contact with the fluid. Furthermore, since the maximum and minimum temperature is given by the applied heating and cooling temperature the temperature gradient is easily interpolated between those values. By measuring the luminescence efficiency vs. temperature response in advance under defined conditions, interpolation functions can be determined.

With a new experimental set-up using a transparent heating plate at the bottom of the convection cell large field of view PIV measurements in horizontal planes were possible. The PIV data contain both horizontal velocity components in planes at different heights. These results are compared with data obtained from three-dimensional direct numerical simulations applying a finite difference method. We report first measurements at Rayleigh number of $10^5$ and $5\times10^5$. Our focus is on the long-term evolution of time-averaged velocity patterns and their spatial correlations. Therefore, we follow the dynamics for several thousand convective time units.

The investigation of the local heat flux is one of the most important tasks in the study of thermal convection. For that reason we need to know both local temperature and velocity fluctuation. In the case of convection cells with high aspect ratio (diameter/height) no large-scale circulation (wind) exists and our interest is focused on smaller coherent flow pattern in horizontal planes parallel to heating and cooling plane. From the combination of temperature and velocity data we will get more information about the interaction of both fields and their influence on pattern formation and resulting convective heat flux. In future we want to measure both field instantaneous by using a combined LIF/PIV setup.

2. Experiment
LIF measurements
For studying turbulent Rayleigh-Bénard convection in water we used a closed cell with dimension of $600 \times 600 \times 20\, \text{mm}^3$ yielding an aspect ratio of $\Gamma = 30$. The transparent non-adiabatic side walls were made of 5 mm thick PMMA. The bottom heating plate (ELKOM) had a
heating power of 1550 W and contained four PT100 thermoresistors controlled by a data logger (Agilent 34970A) with a 20 channel multiplexer (Agilent 34901A). The heating power was controlled with an infinitely variable power supply. The top cooling plate was a flow-through cell containing transparent window pane plates providing optical access to the convection cell. The side walls were also made of PMMA. The cooling liquid was water, driven by a recirculating cooler (Huber Unichiller 012-MPC) with maximum 1200 W cooling power at 15°C. The inlet and outlet temperatures of the flow-through cell were measured with PT100 thermoresistors connected to the data logger. Thus the temperature of the cold enclosure was held constant at 20°C for all measurements. The concentration of rhodamine B in the convective cell was 2 mg/l. The excitation of the dye was carried out by light sheet irradiation with a fully assembled 532 nm laser module with integrated light sheet optics. The laser power was 100 mW continuous wave. Fluorescence images were recorded with a sCMOS camera (PCO edge 5.5), equipped with a Nikkor 35mm f/1.4 manual focus objective (Nikon), at temperature differences $\Delta T = 1.0$ K, 1.8 K, 2.3 K, 2.6 K, 3.3 K and 4.4 K and accumulation rates $\text{Acc} = 1, 2, 4, 8, 16$ and 32 for fixed maximum possible integration time of 20 ms before saturating the CMOS detector. Data processing was performed with ImageJ (National Institutes of Health) by averaging the individual image sequence and subsequently subtracting it from the singles images. Hence the contrast was enhanced (saturated pixels set to 5% and normalization of images) yielding the final temperature field images, gray scaling from the applied cooling temperature (white) to the applied heating temperature (black). The experimental setup is depicted in Figure 1.

![LIF setup showing the Rayleigh-Bénard cell filled with water, laser module above the transparent cooling plate and camera.](image-url)
PIV measurements

For velocity field measurements in air we used a standard planar PIV system from ILA. For a large field of view setup the horizontal laser light sheet was applied through the side wall and the PIV camera was placed under the transparent heating plate (coated with a thin ITO layer) at the bottom of the convection cell (see Figure 2). The aluminum cooling plate operated with cold water (ELKOM) connected to a chiller with a power of 2 kW. As seeding particles DEHS droplets were used. The horizontal light sheet was generated by a Continuum Minilite 30 mJ laser with 1 Hz repetition rate. The PIV images were recorded with a PCO SensiCam SVGA camera.

Fig. 2: PIV setup with air Rayleigh-Bénard cell, laser light sheet from right, PIV camera from below and seeding particle tank above.

3. Results and discussion

Temperature field in water

Temperature fields in water were measured under varying conditions regarding the temperature gradient between hot and cold enclosure of the Rayleigh-Bénard cell. The temperature induced variation of the Rayleigh number calculated by $Ra = \alpha \Delta T gh/va$ was $Ra = 1.1 \times 10^5...5 \times 10^5$, limited by the technical specifications of the heating and cooling system; $\alpha$: thermal expansion coefficient, $\Delta T$: temperature difference between hot and cold enclosure, $g$: acceleration due to gravity, $h$: height of the convective cell, $v$: kinematic viscosity and $a$: thermal diffusivity. To
investigate the applicability of rhodamine B and the accuracy for measuring temperature fields in water, the convective flow was monitored in vertical light sheet orientation for different temperature gradients and accumulation rates. The investigation of the accumulation/averaging rate is so far important since the detection limit of the CMOS is given by its lighting saturation capability due to the integration time, which was found to be 20 ms in the present case. Hence an improvement in image quality can only be achieved by internal accumulation and averaging. But this is a very delicate issue to be handled carefully. The convective flow causes permanent change in local emission which is to be detected. Thus increasing the accumulation rate results in distortion of the effective temperature field and loss of local information, especially if the temperature gradient is increased and the flow velocity rises dramatically. Hence accuracy of temperature field measurements is determined by the trade-off of flow velocity (temperature gradient) and accumulation rate.

Fig. 3: Times series of temperature variations with development of thermal plumes in a vertical plane between heating and cooling plate at Ra = 5 x 10^5.
Apparently, the detection limit of temperature variations in application of rhodamine B is downward limited to $\Delta T = 1$ K, where only variations were detectable at accumulation rate of 32. But the resulted temperature field image seems to be less reliable. First $\Delta T = 5$ K delivered suitable image contrast, also at lower accumulation rate, which further increased for larger $\Delta T$ due to the fact that the luminescence efficiency of rhodamine B largely depended on the applied temperature. It is also quite obvious that the accumulation rate had strong impact on the image quality, especially at small temperature gradients. Increasing the accumulation rate led to increased temperature field contrast and decreased noise of the images, despite the fact that the effective temperature field washed-out for larger temperature gradients. Consequently for the applied integration time of 20 ms frame rates varied from 50 Hz for $\text{Acc} = 1$ to 1.56 Hz for $\text{Acc} = 32$, which becomes critical for large flow velocity due to increased temperature gradient. This has to be considered when evaluating such images and judging the reliability of the resulting temperature field. Finally, it is to be advised to minimize the accumulation rate to the least suitable value to do not lose spatial resolution on smaller time scales.

An example of temperature fluctuation is demonstrated in Fig. 3. A times series over 15 s shows the development of large-scale coherent structures generated by thermal plumes which can intensify the heat flux in the convection cell.

**Velocity field in air**

For PIV measurements in air we used a rectangular convection cell with a size of $460 \times 460 \times 46$ mm. In Fig. 4 snapshots of velocity field in two different horizontal planes are to see. In the plane close to the cooling plate (top of the convection cell) the velocity magnitude is larger than the data from the mid plane in the center of the cell. That means at bottom and top plate we see a more horizontal orientation of the flow while in the mid plane the flow is more vertical directed. Furthermore we can state a very good agreement of the PIV results with direct numerical simulations (DNS). Like the forecast from DNS the instantaneous turbulent velocity field is characterized by flow fronts, rising thermal plumes and local eddy with a high temporal dynamic. The rising hot and falling cold plumes are illustrated in the vertical plane by LIF images in Fig. 3. They are responsible for the vertical flow in the mid plane of the convection cell. From numerical simulation of temperature and velocity field we know that in a fully developed turbulent flow after time-averaging coherent large-scale pattern appear. One hypothesis for these phenomena is the conservation of coherent structures from laminar to turbulent conditions.
Fig. 4: Snapshots of velocity fields in horizontal planes at Ra=5 x 10^5; top: top-plane below cooling plate, bottom: mid-plane, left side: PIV-results, right side: DNS.

The PIV results are compared with data obtained from three-dimensional direct numerical simulations applying a finite difference method at Rayleigh number of 10^4 and 5 x 10^5. Our focus is on the long-term evolution of time-averaged velocity patterns and their spatial correlations. Therefore, we follow the dynamics for several thousand convective time units. On all time scales which we can resolve, a slow evolution of the mean patterns is observable. This is quantified by means of time-windowed averaging and spatial correlations. The analysis reveals a good agreement between experiment and simulation. In Fig. 5 a comparison of the velocity fields
show large-scale coherent flow pattern after averaging 500 snapshots of PIV vector plots vs. 70 and 500 DNS snapshots.

Fig. 5: Coherent flow pattern in time averaged velocity fields: left: PIV over 500 snapshots, middle: DNS over 70 snapshots, and right: DNS over 500 snapshots.

The transformation from a horizontal roll-structure (70 snapshots) to diagonal pattern (500 snapshots) during time-windowed averaging of DNS data we cannot find in the experimental data until now.

References