9.6 Large Scale Rayleigh-Bénard Convection

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Table 9.11. PIV recording parameters for large scale Rayleigh-Bénard convection.

Flow geometry	central crosscut, one half of the convection cell
Maximum velocity	0.4 m/s
Field of view	12.3 m^2
Interrogation volume	$96 \times 96 \times 40\,mm^3$
Observation distance	3.4 m - 5.9 m
Recording method	double frame/single exposure
Recording medium	CCD-camera
Recording lens	$f = 8\,mm$, $f_\# = 1.3$
Illumination	Nd:YAG laser 160 mJ/pulse
Pulse delay	$\Delta t = 30\,ms$
Seeding material	helium-filled soap bubbles ($d_p \approx 1 \ldots 3\,mm$)

9.6.1 Introduction

The application of PIV to measurement of flows on large scales is a challenging necessity especially for investigations of convective air flows. By combination of helium filled soap bubbles as tracer particles with high power quality switched solid state lasers as light sources stereoscopic PIV on scales of more than $10\,m^2$ becomes possible. The technique has been applied to natural convection in a large scale Rayleigh-Bénard facility for the detection of characteristic convection patterns as described in the following.

Turbulent convective air flows are essential not only for many technical applications like for example climatization of vehicle compartments [316, 317, 319, 320] or residential buildings, but also for the warming of the atmosphere and mixing of the oceans [318]. Especially in combination with forced convection, such flows are usually difficult to scale. Therefore large scale PIV at full model size is highly desirable.

9.6.2 Stereo PIV in the Barrel of Ilmenau

One of the best-known experiments to investigate natural thermal convection is the Rayleigh-Bénard experiment, where a fluid is heated at the bottom and cooled at the ceiling of its confinements. Stereoscopic PIV measurements of large-scale Rayleigh-Bénard convection were conducted in the Barrel of Ilmenau, a large scale Rayleigh-Bénard facility. The Barrel of Ilmenau is a cylindrical container with an inner diameter of $D = 7.15\,\mathrm{m}$ and a variable height H of $0\,\mathrm{m} < H < 6.3\,\mathrm{m}$. It is equipped with a heating plate at the bottom and a cooling plate at the top and nearly adiabatic side walls. As a fluid, ambient air is used. The heating plate at the bottom consists of a heating wire in a concrete layer similar to an electrical under floor heating. In order to minimize heat losses through the bottom a thermal isolation layer with a thickness of 300 mm is placed directly below the heating layer. The surface of the heating plate is coated with aluminum foil in order to prevent radiation exchange with the cooling plate and the sidewalls. The maximum surface temperature which can be realized at the floor amounts to 75°C. The cooling plate consists of 16 separate water-cooled segments. They are made of two aluminum-plates with an interconnecting cooling coil and measure 40 mm in thickness. Together with a cooling system and a big water reservoir an accurate regularity of the temperature at the surface of the cooling plate was realized. The maximum temperature deviation over the whole surface is less than 1 K. The inner sidewall is made of a fiberglass-epoxy compound with an embedded thermal isolation layer with a thickness of 160 mm. In order to minimize heat losses it is covered with a heating system for active compensation of heat losses and a further isolation with a thickness of 140 mm. The measurements discussed in the following were conducted at a Rayleigh number of $\mathrm{Ra} = 1.2 \cdot 10^{11}$. The floor temperature was set to 60°C and the ceiling temperature amounted to 20°C. The aspect ratio of the cell was set to $D/H = 2$.

The neutrally buoyant helium filled soap bubbles used as tracer particles for the PIV measurements were generated with two bubble generators and had diameters between 1 and 3 mm. They were injected into the cell through two small holes in the ceiling. For illumination of the tracer particles a quality switched air-cooled double cavity Nd:YAG laser with a pulse energy of 160 mJ was used. The particles were detected with two CCD cameras (Sensicam QE,

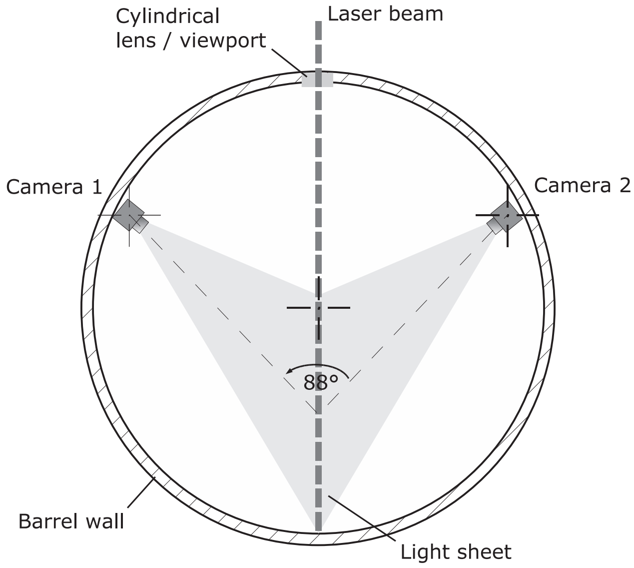

Fig. 9.36. Sketch of the stereo setup for PIV of natural convection in the Barrel of Ilmenau, top view.

PCO) with a Peltier-cooled CCD-chip and a resolution of 1376×1040 pixel in a stereo PIV setup, see figure 9.36 and 9.37. The double frames were recorded at a repetition rate of 2.5 Hz. For evaluation of the velocity vector fields, interrogation windows of 48×48 pixel were used leading to an interrogation window size of $96 \times 96\,\text{mm}^2$. The thickness of the light sheet is thus of the order of the interrogation window size as it is appropriate for highly 3D convective air flow. Multiple pass interrogation was used for calculation of the correlation between the interrogation windows of subsequent images and the correlation maximum was determined with sub pixel accuracy by a 3-point Gauss fit to the correlation peak. In order to further reduce noise, double

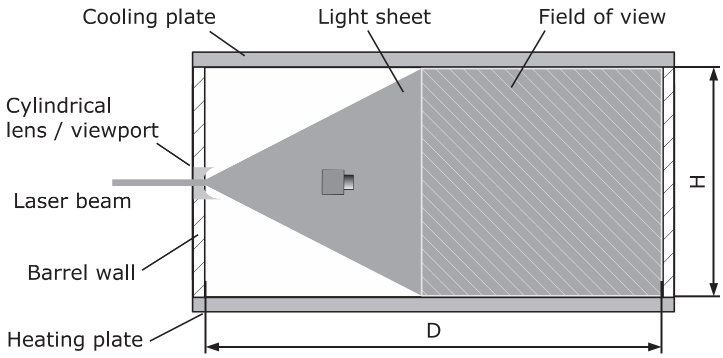

Fig. 9.37. Sketch of the stereo setup for PIV of natural convection in the Barrel of Ilmenau, side view.

correlation was applied. The interrogation window overlap was set to 50%. Since thermal convection in a Rayleigh-Bénard configuration is very sensitive to deteriorations in the symmetry, the optical access to the Barrel of Ilmenau is kept quite limited. In order to couple the laser light into the convection cell, a small viewport has been drilled into the wall and covered with the cylindrical lens, which was used in order to generate a light sheet, see figure 9.36 and 9.37. The thickness of the light sheet was adjusted with a telescope to amount between 3 and 5 cm. Due to the optical restrictions, as already mentioned, the CCD cameras had to be mounted inside of the convection cell. In order to cover one half of the convection cell lenses with a focal length as small as $f = 8\,\mathrm{mm}$ have been used. The angle between the cameras was set to 88°, see figure 9.36, the cameras looking in a backward scattering configuration on the measurement plane, which covered slightly more than one half of the Rayleigh-Bénard cell, see figure 9.37. Here the very high backward scattering efficiency of the helium filled soap bubbles comes into play handy. The overall FOV in this measurement was as large as $12.3\,\mathrm{m}^2$.

Usually in a stereo PIV setup, the CCD chips being tilted with respect to the light sheet plane, a Scheimpflug adapter has to be used in order to focus on the particles in the whole image plane. Estimating the depth of field δ_z for our configuration, however, with a magnification of $M = 1.5 \times 10^{-3}$, a particle diameter of $d_p = 1\,\mathrm{mm}$, and a F-number of $f_\# = 1.3$ yields $\delta_z = 2.6\,\mathrm{m}$. Consequently in this setup there was no need to use a Scheimpflug adapter in order to focus on the particles. Since at aspect ratio $D/H = 2$ a transition of a steady two dimensional flow structure like a single roll into a three dimensional structure of several rolls or toroids with varying directions is expected to occur, the structures changing periodically [321, 322], the aim of our measurements was to capture such structures with our particle images. In order to identify these typical flow structures instantaneous 3C velocity maps as well as averages of 114 velocity fields have been evaluated.

As an example figure 9.38 and figure 9.39 depict the instantaneous and averaged velocity field, respectively, of a single convection roll in the Barrel of Ilmenau. It can be seen clearly that the fluid moves to the right at the bottom towards the barrel wall where it rises up in order to move back to the barrel center at the ceiling. Comparing the homogeneous flow structures in the time averaged vector plots to the instantaneous velocity map reveals thermal plumes, that is, spatially varying local jets from the hot bottom. In addition to toroidal structures, which are dominated by velocity components in the light sheet plane, structures with dominating out of plane velocity components have been detected as well [315].

9.6.3 Conclusions

Combination of neutrally buoyant helium filled soap bubbles as tracer particles with nanosecond laser pulses as light source in a PIV experiment has

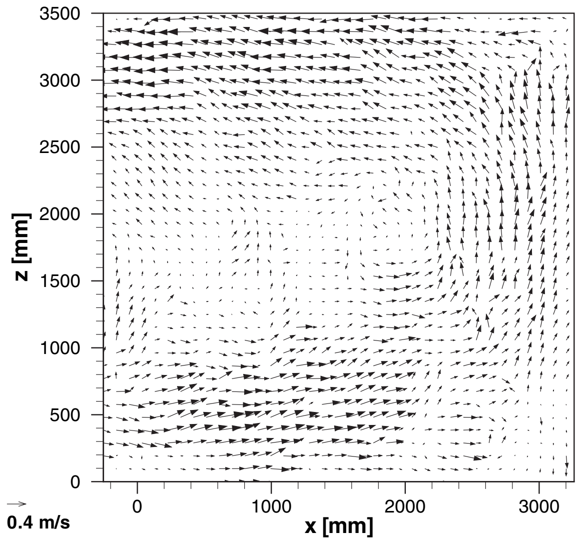

Fig. 9.38. Instantaneous velocity map of a convection roll in the Barrel of Ilmenau at aspect ratio $D/H = 2$. The barrel center is located at $x = 0$. Spatial velocity fluctuations near the hot bottom indicate the existence of thermal plumes.

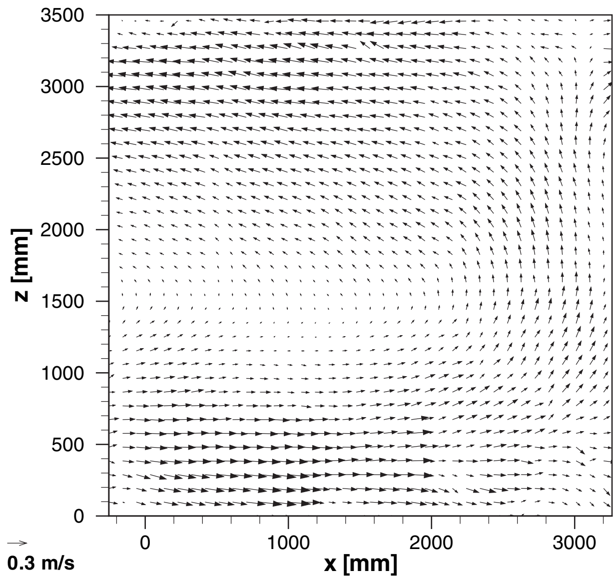

Fig. 9.39. Average of 114 velocity fields of a convection roll in the Barrel of Ilmenau at aspect ratio $D/H = 2$. The barrel center is located at $x = 0$.

been demonstrated to be a very promising approach for measurement of air flow on large scales. The feasibility of the method has been demonstrated by stereoscopic PIV of natural convection in a large scale Rayleigh-Bénard experiment on a field of view as large as $12.3\,\mathrm{m}^2$. In addition to the exceptionally large scattering efficiency the high backward scattering efficiency of the tracer particles comes into play as an advantage of the helium filled soap bubbles in the presented stereo setup.

Measurement of natural convection in the Barrel of Ilmenau by large scale PIV made possible identification of characteristic flow patterns in RB convection. At aspect ratio $D/H = 2$, as expected, different kinds of flow structures could be detected. Along with toroidal structures like single or dual convection rolls, structures with dominating out of plane velocity components have been observed as well. For verification or falsification of model predictions of Rayleigh-Bénard convection in the Barrel of Ilmenau by PIV, however, the cameras should be installed preferably inside the insulating walls in order neither to deteriorate the flow nor to break the thermal shielding of the convection cell.

Even though discussed for application to basic research facilities here, large scale PIV involving helium filled soap bubbles could be a mighty tool for many technical applications involving air flow on large scales as well, like e.g. ventilation of cars, trains, aircraft cabins [315], clean rooms, or even wind tunnel testing.