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Formation of turbulent superstructures in Rayleigh-Bénard convection

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Abstract In this paper we present the spatio-temporal dynamics of large-scale structure formation in Rayleigh-Bènard convection at high aspect ratio. We have measured velocity and temperature fields in a rectangular Rayleigh-Bènard cell with aspect ratios Γ=10, Γ=30 and at $Ra=3x10^5$ using PIV and LIF in air and water. The resulting flow pattern and structures in the temperature field are compared with numerical simulation. Furthermore we introduce thermal convection experiments with a large Ra range using pressurized air and SF6.
Keywords: PIV, LIV, thermal convection

1 Introduction

Many turbulent convection processes, in particular in nature, are present in extended layers and show hierarchies of regular ordered flow patterns although the corresponding Rayleigh (Ra) and Reynolds (Re) numbers suggest a fully developed turbulence. Coherent structures and large-scale circulations occur e.g. in passenger cabins of aircrafts and high-speed trains, in cloud formations of the earth atmosphere and in the chromosphere of the sun.

We want to identify the time and length scales on which the patterns evolve and investigate their Rayleigh number dependence in small-scale laboratory experiments. These allow us to study the robustness of the flow patterns with respect to non-Boussinesq effects. Based on the experiments in air, water and in future in sulfur hexafluoride (SF6) and numerical simulations, we want to develop also reduced models which describe the patterns by a few dominant degrees of freedom. The necessity of broad ranges of Rayleigh numbers for systematically investigation of the flow pattern in convection cells with large aspect ratio can be easily achieved by using pressurized SF6 in a cylindrical vessel called SCALEX (Scaled Convective Airflow Laboratory Experiment, Fig. 1) (Körner et al. 2011).

In order to adapt the flow measurement technique using visualization and particle image velocimetry (PIV) and to compare the measured flow pattern with direct numerical simulations (DNS) at low Ra, we started the investigation in a convection cell with aspect ratio Γ = 10 filled with air at normal pressure, see Fig 2. In a second Rayleigh-Bènard experiment with water as working fluid laser induced fluorescence (LIF) was applied to visualize the spatio-temporal temperature field.

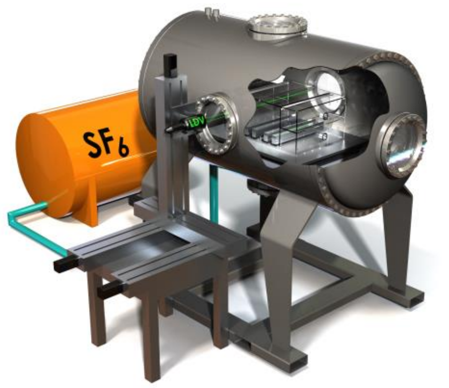

Fig. 1 Sketch of SCALEX (left) and picture of the whole facility (right). The pressure vessel of 2m x 1.m dimension works with pressurized SF6 up to 10bar. The size of the model cell is limited to 0.75m x 0.5m x 0.5m. The pressure vessel is connected with a SF6 storage system (orange part in right picture).

2 Experiments with PIV

The air convection experiment is performed in a rectangular Rayleigh-Bènard cell with the dimension of *L x W x H*=460mm x 460mm x 46mm. This convection cell consist of a frame of PMMA with a semi-transparent metal-coated glass plate (Hillesheim GmbH, Waghäusel) as electrical bottom heating and a water-cooled aluminum plate as top cooling. In both plates temperature sensors are integrated. With a temperature difference of 32 K we reach a maximum Rayleigh number of $Ra=3 \times 10^5$ with an aspect ratio of $\Gamma=10$. Using infrared camera technique we measured a homogeneous temperature distribution at the semi-transparent glass plate with spatial deviations $\Delta T < 0.1$ K as well as at the top aluminum plate.

We record the flow pattern by a 2D particle image velocimetry (PIV) system. The horizontal orientated laser light sheet (double-pulse Continuum MiniLite 532nm, 30mJ@10Hz) is applied from the left side of the convection cell and illuminates different measurement planes between cooling and heating plate. The PIV camera (PCO SensiCam SVGA) is placed under the convection cell, see Fig. 2. The seeding particles are generated by a smoke generator and stored in a glass tank above the cell. This storage tank is connected with the convection cell by a thin flexible tube in order to not disturb the flow inside the cell. The field of view of the PIV measurement amounts to 150mm x 150 mm.

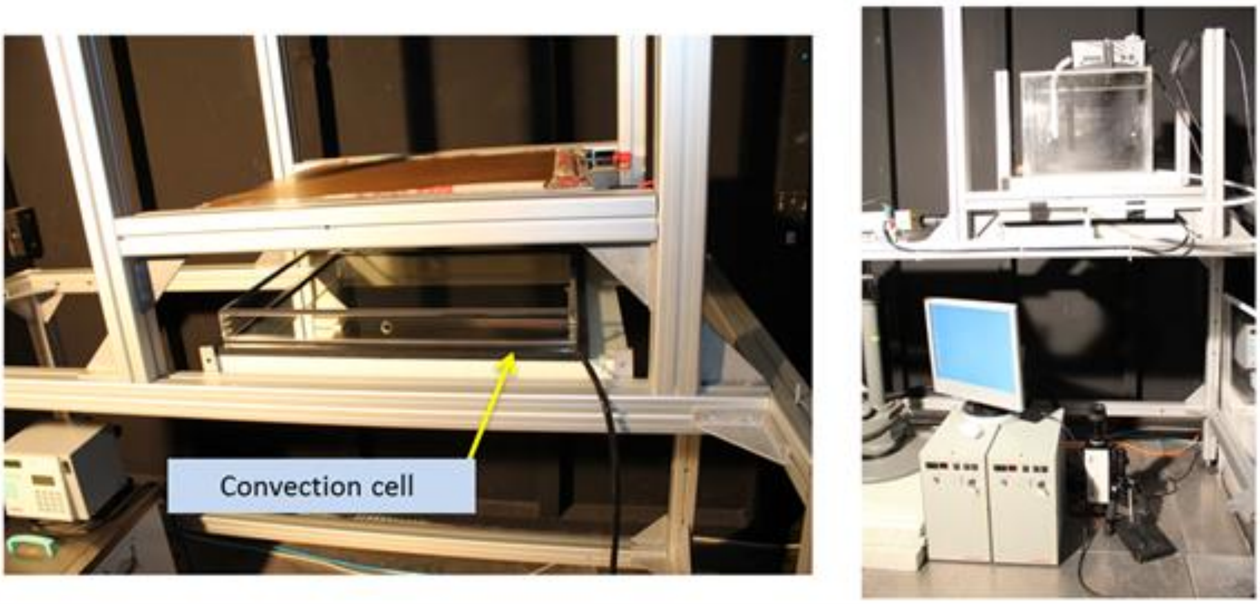

Fig. 2 Experimental set-up of the air cell: left – Details of the convection cell made of PMMA with semi-transparent electrical heating plate at the bottom and aluminum plate with water cooling at the top, right – Convection cell with PIV camera at the bottom, light sheet laser at the left side und smoke tank with smoke generator at the top.

3 Experiments with LIF

Turbulent Rayleigh-Bénard convection is a less-studied phenomenon in large aspect ratio convection cells. Furthermore, the existence of temperature superstructures in turbulent convection is only known from direct numerical simulations (DNS) (Fig. 5) and was not experimentally confirmed so far. Against this background we investigated large-scale circulation in turbulent convective flow in water, applied to a Rayleigh-Bénard cell with large aspect ratio $\Gamma= 30$ and Rayleigh numbers about $Ra = 10^4 \ldots 10^6$.

In a second experiment thermal convection in water is performed in a rectangular Rayleigh-Bènard cell with the dimension of L x W x H = 600mm x600mm x 20mm. This convection cell consist of a frame of PMMA with an electrical heating inside an aluminum plate at the bottom and a transparent water-filled cooling glass plate at the top, tempered by an internal water circuit which is connected to a thermostat.

With the application of laser induced fluorescence we introduced temperature field measurements under the given conditions for the first time. Hence the major aim of this work was on the one hand checking the applicability of temperature field measurements and the accessible thermal resolution (minimum detectable temperature difference ΔT) in turbulent flow by LIF (see Sakakibara & Adrian 2004) and thus the investigation of changing conditions from weak to strong turbulence, may yielding long term stabilization/oscillation of the convective flow. The Rayleigh number was controlled by adjusting the temperature gradient between hot bottom and cold top enclosure of the convection cell about $\Delta T = 0 \ldots 35$ K.

The convective heat flow is monitored by 2D PIV and compared with contactless temperature field measurements by LIF (sCMOS camera PCO Edge 5.5 with 542nm low pass optical filter), based on temperature induced fluorescence intensity variations of Rhodamin B added to the water. Both, PIV and LIF, were measured in 532 nm light sheet irradiation (Nd-YAG 30mJ @10Hz and 100mJ cw) in the horizontal and vertical plane of the convective cell. As tracer for PIV 1µm Nylon particles have been used.

4 Results

In Fig. 3 snapshots from PIV measurements in the air cell and DNS are illustrated. Both velocity fields show the same characteristic large-scale flow structures: flow fronts, rising thermal plumes and local eddies. They are taken at 5mm distance from the top plate. We can summarize that the PIV results validate the DNS very well. In both cases we observe the typical building blocks of the structure formation in turbulent convection which are formed in the vicinity of the heating and cooling plates.

A central task for our future work is to track the hidden regular patterns and their slow morphological change with increasing Rayleigh number in very-large aspect ratio systems systematically. Exactly this task requires the application of pressurized sulfur hexafluoride as a working fluid.

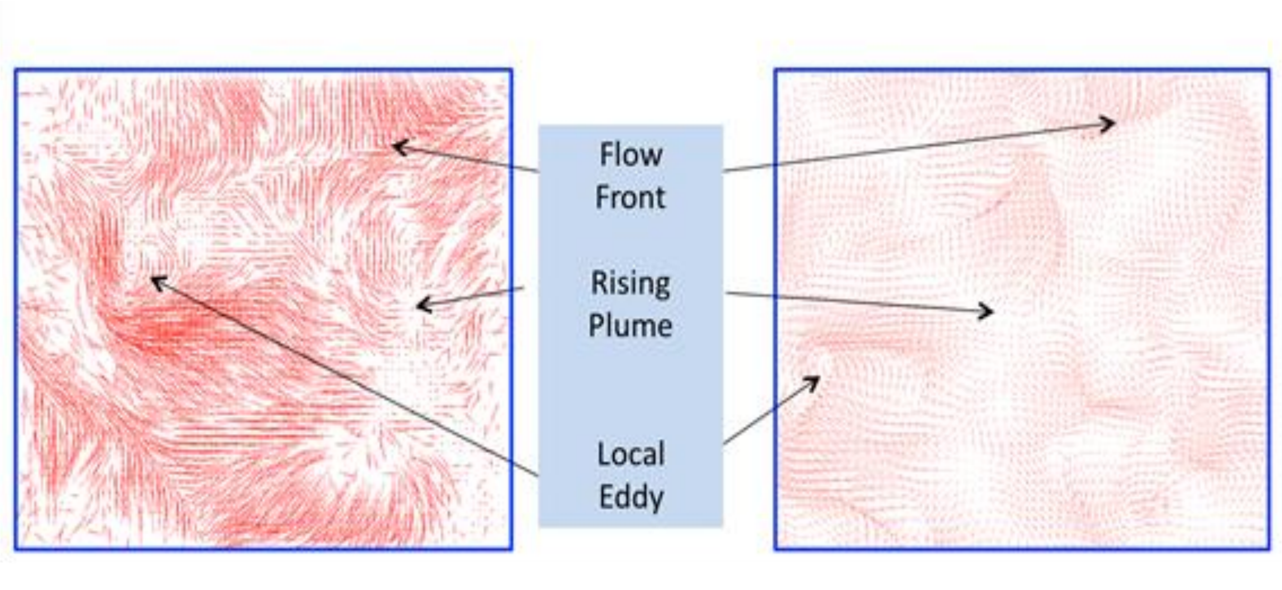

Fig. 3 Snapshot of the horizontal velocity field (left: PIV, right: DNS) with large-scale flow structures: flow fronts, local eddy and rising thermal plum.

One of the main challenges in experimental studies in turbulent convection is the combination of velocity and temperature measurements since the temperature is the active scalar which drives the fluid motion. As it can be seen in Fig. 5 the structure of the temperature field varies significantly when compared between heated bottom plate and mid plane as it is illustrated in the two contour slice plots of instantaneous snapshots at the Rayleigh number of $Ra = 3 \times 10^5$. In the left panel of the figure one clearly observes the line-like plume filaments which detach from the heating plate and rise into the bulk causing partly the flow structures which we have detected in the PIV analysis. These plumes decay due to turbulent diffusion and the skeleton of ridges gets partly lost in the center of the cell as shown in the right figure.

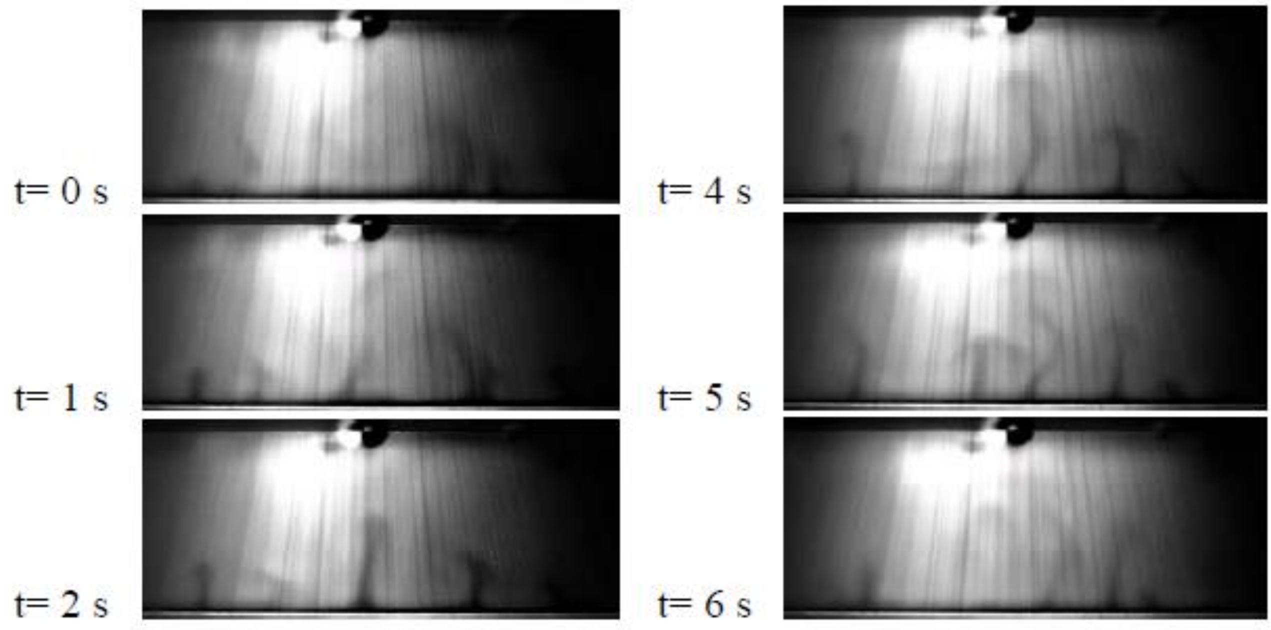

Fig. 4 Time series of temperature field measurement in vertical direction show thermal plume development at the heating plate.

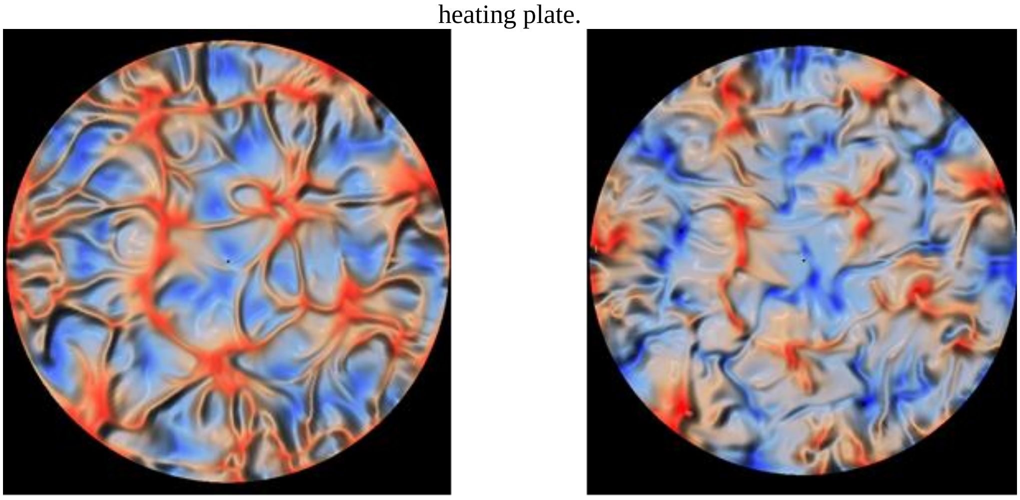

Fig. 5 Top view of DNS stream lines in a convection cell at *Ra* = $3x10^5$, *Pr* = 0.7 and □ = 12. Left: temperature in the thermal boundary layer, right: temperature in the mid plane (Bailon-Cuba et al. 2010).

Figure 4 shows a time-series of a temperature field measured with LIF in vertical light sheet orientation. The dark plumes arising from the hot bottom enclosure at 30°C are clearly visible. The temperature of the cold enclosure was 20°C. The LIF measurements of the horizontal temperature field in different heights are currently in progress and the results will be used for the validation of the superstructures obtained from DNS (Fig. 5).

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