# DENSE LAGRANGIAN PARTICLE TRACKING OF TURBULENT RAYLEIGH BÉNARD CONVECTION IN A CYLINDRICAL SAMPLE USING SHAKE-THE-BOX

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We present spatially and temporally resolved velocity and acceleration measurements of turbulent Rayleigh-Bénard convection (RBC) covering the complete volume of a cylindrical sample with aspect ratio one. Using the *Shake-The-Box* (STB) Lagrangian particle tracking (LPT) algorithm [1], we are able to instantaneously track up to ~ 600,000 particles in the complete sample volume (~ 1 m³), corresponding to mean inter-particle distances of 8 Kolmogorov lengths. The data assimilation scheme *FlowFit* [2] with continuity and Navier-Stokes-constraints is used to interpolate the scattered velocity and acceleration data by continuous 3D B-Splines in a cubic grid, enabling to recover the smallest flow scales. The frame rate was chosen to be at least 7 times faster than the Kolmogorov time scale. In the presentation, we show Lagrangian and Eulerian visualizations (see e.g. Figure 1) of the large scale circulation (LSC) as well as small scale structures, such as thermal plumes and turbulent background fluctuations and unveil the dynamics of their complex interplay. Rare dynamic events, such as cessations and reorientations of the LSC will be presented in addition to combined and conditioned Lagrangian and Eulerian statistics of turbulent quantities.

The convection cell used in our study has a height and diameter of 1.1 m and uses air at atmospheric pressure as working fluid. Rayleigh numbers up to $Ra = 2 \cdot 10^9$ could be reached at $Pr = 0.7$. We used helium filled, neutrally buoyant soap bubbles (HFSBs) with a diameter of 400 µm as tracer particles. They were produced with an orifice nozzle [3] in combination with a bubble film solution developed specially for this purpose. The latter allows for a significantly enhanced lifetime and hence experimental runs up to 30 minutes. During the measurements, the sample was illuminated through the transparent cooling plate by an array of 849 pulsed high-power LEDs, covering the complete sample. Particle images were captured in chunks of varying length by an inline ensemble of six scientific CMOS cameras, which covered an aperture angle of approx. 80°.

The complex dynamics of the LSC in turbulent RBC has gained much attention in the last decades; however, direct volumetric measurements of the LSC are still rare. While tomographic PIV [4,5] or LPT [5,6] were employed already in the past, measurements at full spatial and temporal resolution covering the whole sample were still lacking. Figure 1 shows an instantaneous velocity field from a measurement at $Ra = 5.4 \cdot 10^8$. Clearly, the LSC can be spotted in the data when looking at the color coded vertical velocity. A novelty to optical flow measurements of RBC is the complete resolution of the turbulent flow structures, visualized by iso-surfaces of the Q-criterion. Not visible in the image is the corresponding temporal resolution, which enables observation of the dynamic interaction between small and large scale turbulent structures. This work was supported by the *Deutsche Forschungsgemeinschaft* (DFG) through Grant No. SCHR 1165/5-1 as part of the Priority Programme on Turbulent Superstructures (DFG SPP 1881).

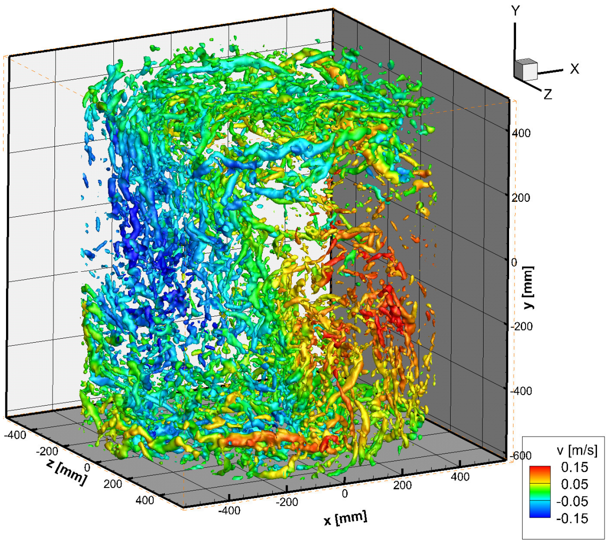


**Figure 1.** Visualization of an instantaneous turbulent velocity field from RBC at $Ra = 5.4 \cdot 10^8$ measured with STB and further processed with FlowFit. Depicted are the iso-surfaces of the Q-criterion, $Q = 4\ s^{-2}$, and the vertical velocity (colour).

## References

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