Analysing turbulent structures of a Rayleigh-Bénard convection in a cubic cell based on Particle-Tracking-Velocimetry

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Abstract:
We present recent results on the analysis of turbulent flow structures in a cubic Rayleigh-Bénard (RB) convection cell based on measurement data processed by Particle-Tracking-Velocimetry (PTV) techniques. The RB convection is a canonic flow suited to study the principles of turbulent thermal convection because of its geometrically simple configuration, i.e. a cylindrical or rectangular shaped container which is cooled from above and heated from below (Brown and Ahlers, 2006). The latter cause an interplay of warm fluid rising up from the heating plate and cold fluid descending from the cooling plate. The configuration of interest is the cubic RB cell since the dynamics of the flow are guided by meta-stable (Wei, 2021) large scale circulations (LSC). In this case, the LSC are circular flow structures oriented along one of the cell diagonals which are rotating clockwise or counterclockwise along the present cell diagonal. The dynamics of the LSC is meta-stable because its current orientation only lasts for a limited time window. Vasiliev et al. (2016); Bai et al. (2016); Ji and Brown (2020) showed the LSC statistically disorder and then reorder in a different meta-stable configuration due to flow reversal events.
To analyse the flow dynamics leading to the reversal events, we present and discuss optical, non-invasive measurements of a turbulent Rayleigh-Bénard convection in a newly constructed cubic cell. The cell is equipped with an optically transparent cooling plate in order to be able to illuminated the measurement volume from above. This arrangement allows the flow to be observed through the side walls of the cell, which are made of glass, with a viewing angle of up to 360°. The cooling plate is made of sapphire glass and the heating plate is made of aluminium. Both materials allow a homogeneous temperature distribution due to their high thermal conductivity. During the measurement, the cell is filled with water to reach a Prandtl number of Pr ≈ 6.9. A RB convection in the hard turbulence regime is realized by achieving a Rayleigh number of Ra $\approx 3 \cdot 10^8$. Vishnu et al. (2020) suggests that in this regime the time scale to observe a reversal event is about 2 to 3 hours because the LSC contains a lot of turbulent kinetic energy which makes the LSC quite stable against reorientation. To make sure that at least two reversal events fall within the measurement they are extended to up to 8 hours. Thereby, for the flow visualisation high-quality polyamide particles from LaVision with a mean diameter of $60\,\mu$m are seeded in the flow. The particles have a density of $\rho = 1.001\,\rho_{H_2O}$, to ensure buoyancy neutral seeding particles.
In the last years Particle-Tracking-Velocimetry (PTV) became one of the most popular optical, non-invasive flow measurement techniques. PTV reconstructs the 3D path of individual seeding particles in a Lagrangian frame. Therefore, even complicated turbulent flow structures occurring on large as well as on small scales can be observed without interfering the flow. To determine particle trajectories from the measurement data our novel open-source probability-based Particle-Tracking-Velocimetry framework named pyPTV is applied. The framework will be freely available in mid-2023 and is completely written in Python. It allows the user to perform a full PTV routine on a given data set including image-processing, calibration and PTV algorithms including post-processing tools like track repairing and backtracking. Consequently, the pyPTV framework can be used to interpolate Eulerian velocity flow fields on Cartesian coordinates from the processed Lagrangian particle trajectories. An example of the particle trajectories obtained with pyPTV and a section of an instantaneous Eulerian velocity field along the LSC diagonal reconstructed from the particle trajectories is shown in Fig. 1.
At the conference, we want to present the analysis of the LSC dynamics based on Eulerian flow fields extracted from PTV trajectories. Here, the interplay between primary and secondary circulation structures is studied by applying a Proper-Orthogonal-Decomposition (POD). In addition, the dynamics of the LSC inside the cubic RB convection upon observing flow reversal events will be investigated by analysing the turbulent kinetic energy budget of the flow.

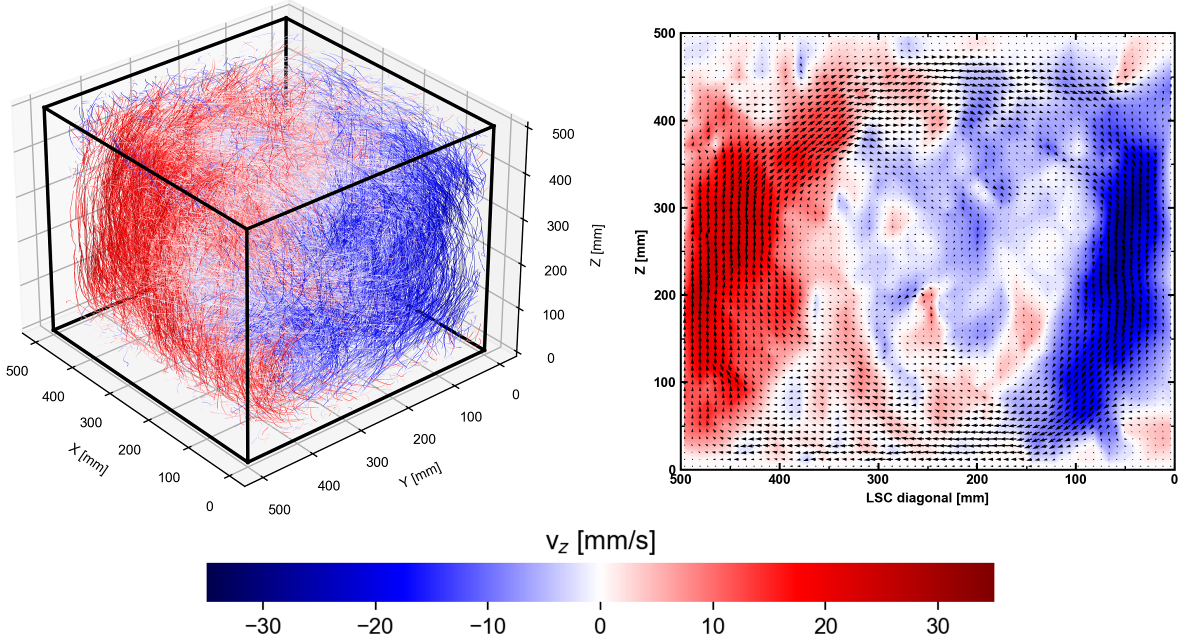

Figure 1: **Left:** reconstructed particle trajectories of an experimental RB convection with Ra $\approx 1 \cdot 10^{10}$ and Pr ≈ 6.9. **Right:** instantaneous Eulerian velocity field along the LSC diagonal ($X = Y$) reconstructed from the particle trajectories. Both plots are color coded by the vertical velocity component v_z.

References

Bai K, Ji D, and Brown E (2016) Ability of a low-dimensional model to predict geometry-dependent dynamics of large-scale coherent structures in turbulence. *Physical Review E* 93:023117

Brown E and Ahlers G (2006) Rotations and cessations of the large-scale circulation in turbulent rayleigh–bénard convection. *Journal of Fluid Mechanics* 568:351–386

Ji D and Brown E (2020) Low-dimensional model of the large-scale circulation of turbulent rayleigh-bénard convection in a cubic container. *Physical Review Fluids* 5:064606

Vasiliev A, Sukhanovskii A, Frick P, Budnikov A, Fomichev V, Bolshukhin M, and Romanov R (2016) High rayleigh number convection in a cubic cell with adiabatic sidewalls. *International Journal of Heat and Mass Transfer* 102:201–212

Vishnu VT, De AK, and Mishra PK (2020) Dynamics of large-scale circulation and energy transfer mechanism in turbulent rayleigh-bénard convection in a cubic cell. *Physics of Fluids* 32:095115

Wei P (2021) The persistence of large-scale circulation in rayleigh–bénard convection. *Journal of Fluid Mechanics* 924