

Observed dust devil-like flow structures in large-scale turbulent Rayleigh-Bénard convection

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ABSTRACT

Turbulent Rayleigh-Bénard (RB) convection, a fluid layer heated from below and cooled from above, might be an appropriate tool to reproduce flow phenomena as occurring in a convective atmospheric boundary layer. One of these phenomena is the appearance of so-called dust devils, vortex like flow structures with typical dimensions up to a few tens of meters in diameter and up to a few hundreds of meters in height. Unlike their big brothers, the tornados, start to evolve close to the ground, but the physics of their evolution are still not fully understood. Since field measurements of dust devils are extremely hard to realize (due to their very rare and spontaneous appearance at arbitrarily varying locations), continuous flow measurements in large-scale laboratory experiments may help to overcome this problem. Such measurements in flows of several m^3 in volume require optical measurement techniques like particle tracking velocimetry which gains access to the 3-dimensional Lagrangian velocity field. Special attention has to be drawn to the particle seeding of the flow and the imaging of particles. Particles must have neutral density compared to the fluid, and must be large enough to be detected by cameras over a range of several meters. They also should exhibit a prolonged lifetime.

In this study, we present experiments conducted in the “Barrel of Ilmenau”, the world-wide largest Rayleigh-Bénard laboratory experiment with 7.15 m in diameter and up to 6.3 m in height using air as working fluid. Neutrally-buoyant helium-filled soap bubbles were injected into the flow and tracked using four cameras. Illumination was carried out with five high-power LEDs in pulsed mode. Reconstruction of the Lagrangian velocity field was performed with Shake-The-Box algorithm. Thus, the major focus of the presented work was to get access to the entire volumetric Lagrangian velocity field in the convection cell on a very long time. Our aim is to discover very rare flow events in turbulent convection, like e.g. dust devil-like vortices or other turbulent superstructures. Measurement data was analyzed to conclude about the applicability of particle tracking velocimetry as suitable measurement technique for large volumetric flows. Finally, an example of a discovered dust-devil like vortex is presented in detail.

1. Introduction

Flow studies in extended experimental setups, spanning several meters in dimension, most likely lack of probing the complete volume. To reliably conclude about the momentum transfer, it is essential to measure the velocity field in whole space, especially in all three dimensions

simultaneously over time. Several methods like pointwise (if not scanned) laser Doppler anemometry (LDA) (Durst et al., 1981), thermistor probes (Keplinger et al., 2006) or hot-wire technology (Lomas, 2011), and particle image velocimetry (PIV) (Adrian & Westerweel, 2011; Raffel et al., 2018) and particle tracking velocimetry (PTV) (Dabiri & Pecora, 2020; Hoyer et al., 2005) in 2D and 3D have proven their applicability and reliability for measuring the flow velocity over the last decades, among others (Dracos, 1996; Nabavi & Siddiqui, 2010; Ristić et al., 2004). Actually, the dimensions of the experimental setups are limited due to recent aspects. To study flow physics in detail, it is vital to apply an efficient particle seeding, homogenous and continuous over time, and the detection of the whole volume. The latter is particularly challenging towards the imaging system focusing the complete volume. But, also the illumination of the whole volume has to be preferably homogeneous that scattered light from the seeded particles do not locally overflow the CCD/CMOS detectors of the imaging system. Strong undulations of locally scattered light intensity lead to further uncertainty when analyzing those images. To study large dimensional flows, PTV is the most recent technique. At least two cameras image the whole volume and particle trajectories are reconstructed by triangulation of the individual images of the cameras. A very convenient and well-studied flow experiment is the Rayleigh-Bénard (RB) set-up, an idealized model experiment of free thermal convection. It consists of a fluid layer which is heated from below and cooled from above. In many cases, the fluid layer is confined by a sidewall/sidewalls (Bénard, 1901; Ostrach, 1972; Rayleigh, 1916). The present study has been undertaken in a large-scale Rayleigh-Bénard experiment which is called the “Barrel of Ilmenau” (www.ilmenauer-fass.de). The width-to-height ratio, quite often referred to as aspect ratio was set to $\Gamma=3$, since flow characteristics are well known from measurements on smaller scales (Kästner et al., 2018; Moller et al., 2021), but also from numerical simulations (Emran & Schumacher, 2015; Sakievich et al., 2016). This configuration confines a volume of $\sim 100 \text{ m}^3$ and is quite challenging to perform PTV in the whole bulk of thermal convection. Nevertheless, it potentially allows new insights into thermally driven convective flows, especially the application of PTV on larger domains.

Thermal convection is characterized by heat and momentum transfer due to thermally induced density fluctuations within a fluid. Rayleigh-Bénard convection is the most common and deeply investigated standardized model experiment which applies only very few boundary conditions: a closed convection cell, uniformly heated from below and uniformly cooled from above, with adiabatic side-walls. The temperature gradient between top and bottom enclosure induces a volumetric force into the fluid, which is aligned opposite to the vector of gravity. With increasing magnitude of temperature difference, the convective flow develops from laminar, steady rolls via time-dependent patterns, to a fully turbulent flow. The dimensionless control parameter of

thermal driving is the Rayleigh number, $Ra = \alpha \Delta T g h^3 / \nu \kappa$; α : thermal expansion coefficient, ΔT : temperature difference between hot and cold enclosure, g : acceleration due to gravity, h : height of the convection cell, ν : kinematic viscosity and κ : thermal diffusivity. With this background, we consider Rayleigh-Bénard convection as a perfect candidate to investigate new flow measurement techniques. The original purpose of this study was primarily the development and the validation of a large-scale flow measurement technique and secondarily the investigation of the global velocity field with its particular coherent structures. The presented approach is discussed in detail on the example of a dust devil-like vortex (Sinclair, 1969, 1973).

2. Experimental procedures

The convection cell “Barrel of Ilmenau” has a cylindrical shape with a diameter of 7.15 m. The maximum height, meaning the distance between the heating and the cooling plate amounts to 6.30 m. For the measurements reported here we set a height of 2.38 m corresponding to an aspect ratio $\Gamma=3$. The bottom and top plate were heated and cooled to specific temperatures, respectively, applying Rayleigh numbers of about 2×10^{10} which means a fully developed turbulent flow. The wall was equipped with an active compensation heating system to keep adiabatic boundary conditions (Du Puits et al., 2013). Tracking particles were neutral-buoyant helium filled soap bubbles with a diameter of about 0.5 cm. Two particle generators were applied, continuously seeding the flow diametrically from the wall into the bulk, located in a height of 1 m above the heating plate. Four cameras (Jaytec) were applied to record the particle motion. The cameras were equipped with 8.5 mm lenses (LM8XC KOWA) with large depth of focus to span nearly the entire volume of the convection cell, focused to the center of the convection cell. Illumination of the particles was applied with five high power LEDs (Luxeon). One LED was placed in the middle between the cameras and the other four to the left and to the right (see Figure 1). The seeding was oriented to the back of the convection cell like the LEDs on right and left side. Back orientation of the LEDs prevented direct light into the cameras and increased reflected light intensity from soap bubbles into the cameras. Back orientation of the seeding directed the soap bubbles more to the back, i.e. into the common field of view of the four cameras. Hence particles in the front of the convection cell do not allow particle triangulation and thus particles are subordinated in this region. More details on seeding and geometrical issues are discussed in (Loesch & du Puits, 2020, 2021). Figure 1 depicts a sketch of the experimental setup in 3D side and 2D top view. The cameras and LEDs were synchronized with a function generator at 10 Hz recording speed. Recording times were up to two hours per run. The camera images were processed with commercial software package DaVis. First processing step of the raw images was the background removal by

subtracting a sliding average of 20 images from each individual image of the time-series. Subsequently, a Gaussian blur filter was applied to smear the particle images and to virtually increase the particle size. The filter also homogenizes local background fluctuations. A larger particle size is vital for the particle tracking algorithm to successfully detect and triangulate them. A further advantage of the Gaussian blur filter is the homogenization of the particle illumination level since soap bubbles may show two reflexes on opposite site which may be interpreted as two particles. Particle tracks were then reconstructed with Shake-The-Box (STB) algorithm (Schanz et al., 2016).

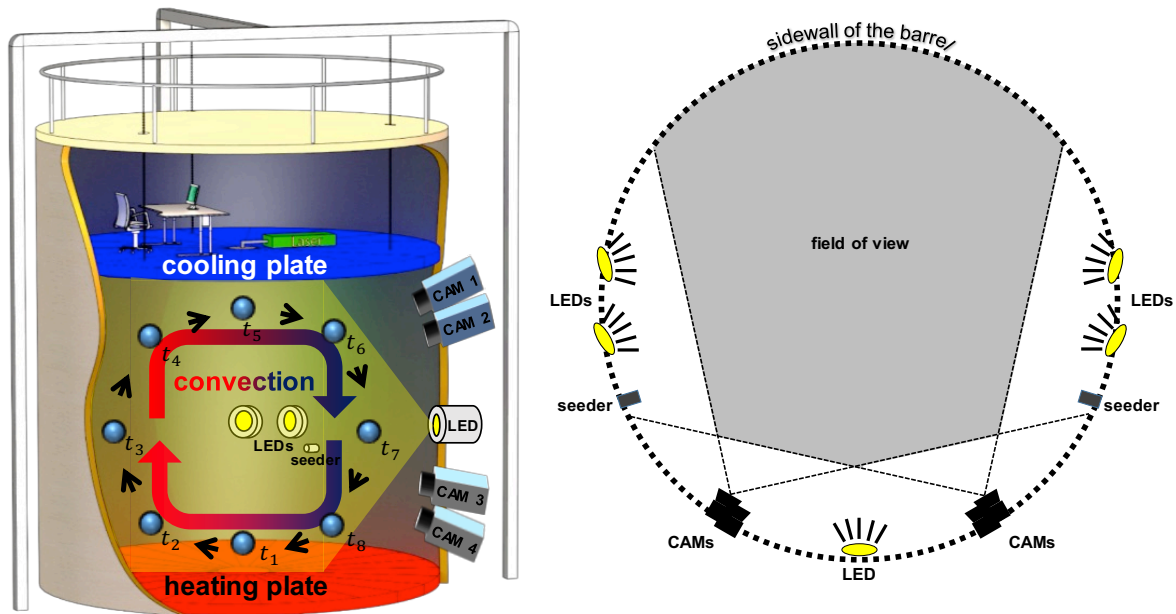


Fig. 1 Sketch of the experimental setup at the “Barrel of Ilmenau”. Left: 3D view from the side. (One soap bubble at different time-steps t represents the tracking of the mean thermal convective flow by four cameras. The flow is triggered by density fluctuation of air between the heating plate at the bottom and the cooling plate on top of the convection cell. Right: Schematic from top view.

For STB procedure a suitable cut-off intensity was set to level out the residual background. Right prior or after the measurement a volumetric calibration (pinhole model) was performed by triangulation of a custom 2D calibration pattern which was recorded randomly in 30 different positions within the convection cell. Afterwards a volume self-calibration algorithm was performed to further increase the accuracy (Wieneke, 2018). Particle images were evaluated in a volume of about 6 m diameter around the central axis of the cell, since the particle density is rather low near the sidewall the reconstruction of sufficiently long tracks often fails. In a next step, the particle tracks corresponding to the Lagrangian perspective on the flow field were translated into

the Eulerian perspective by binning the individual particle velocities onto a regular grid. The sub-volume size was set to 528 voxels and reassembled by 83.33 % overlap leading to a final grid spacing of 88 voxels which equals a spatial resolution of 190 mm. In fact, the binning generates a spatially averaged Eulerian field which diminishes the small scale turbulent structures, but emphasizes the large coherent structures that are aimed to investigate by this technique. More details on the experimental setup and procedures can also be found in (Loesch & du Puits, 2020, 2021). Further data processing, like e.g. the probability density functions of velocity or acceleration was directly processed from the Lagrangian data using Matlab code.

3. Results and Discussion

First of all, we evaluated the quality of the reconstruction of the 3D particle positions and the computation of the particle tracks, i.e. how much particles lead to successful particle tracks. Typically, the ratio between the number of 3D particles and active tracks varies between 0.19 and 0.53 per time-step, whereas the ratio of newly added active tracks to apparent active tracks per time-step varies between zero and 0.13. Table 1 summarizes the experimental boundary conditions, i.e. temperatures of the cooling plate T_{cp} , temperatures of the heating plate T_{hp} , the temperature differences ΔT between cooling and heating plate and the duration of the measurement. Again, the table contains the particle statistics of each experiment, i.e. mean and maximum values of active tracks (at) that could be reconstructed, mean and maximum value of total amount of 3D particles (3Dp) that could be detected per time-step, mean value of newly appearing tracks in each time-step as well as the ratios of active tracks to 3D particles and new tracks to active tracks. Since we do not have insight into the internal parameters of the STB/DaVIS software, we cannot finally judge, whether the quality of the particle images is too poor for triangulation or the internal parameter of the STB algorithm may not fully appropriate for our specific task. Quite recently, a novel kernelized PTV algorithm has been introduced by Yang and Heitz (Yang & Heitz, 2021) that we consider for using in some further data analysis.

Our camera set-up enables us to monitor particle tracks in a volume of 79.3 m³ (the total cell volume amounts to 95.6 m³) Active tracks are considered as tracks that exist for at least three time-steps. Over all experiments and considering a homogeneous distribution of particles, the average particle density reassembled to active tracks varies between 0.7 m⁻³ and 22.6 m⁻³ per time-step, and the maximum particle density varies between 2.4 m⁻³ and 84 m⁻³ per time-step. Assuming an almost homogeneous distribution of the tracks in space, this is a sufficient amount to investigate the global flow or local coherent flow structures of larger decimeter scale.

Table 1 Summary of experimental boundary conditions and corresponding data from evaluated particle images.

#	T_{cp} [°C]	T_{hp} [°C]	ΔT [K]	Ra [10^{10}]	time [s]	active tracks (at)		3D particles (3Dp)		new tracks (nt)	at/3Dp	nt/at
						mean	max	mean	max	mean	mean	mean
1	15	25	10	1.45	5200	540	2388	1018	4076	54	0.53	0.10
2	15	25	10	1.45	5803	391	1131	1003	2682	52	0.39	0.13
3	15	25	10	1.45	4785	1790	6664	3378	12875	12	0.53	0.01
4	15	25	10	1.45	7230	788	3336	1667	6390	69	0.47	0.09
5	20	30	10	1.34	7405	685	2087	3585	14327	2	0.19	0.00
6	15	30	15	2.09	6173	591	2441	1325	4812	54	0.45	0.09
7	15	30	15	2.09	7000	980	3000	1916	5964	4	0.51	0.00
8	15	35	20	2.68	6880	166	737	550	2153	3	0.30	0.02
9	15	40	25	3.23	5381	167	818	469	2281	20	0.36	0.12
10	15	45	30	3.73	6147	56	367	189	916	8	0.30	0.14

Another aspect of interest is the lifetime of particles which is vital to obtain as long as possible particle tracks. This was already discussed in (Loesch & du Puits, 2021), but on much shorter time-scales. To conclude about lifetime and stability of soap bubbles the frequency of occurrence of 3D particles, active tracks and new tracks is plotted as function of temperature difference in the left subfigure of Figure 2. It can be seen that the lifetime of the bubbles decreases with the temperature difference between the heating and the cooling plates. This can be explained by a higher typical velocity, and hence, a higher probability to collide with the walls and to burst. Moreover, the lifetime generally drops with the temperature of the surrounding air and as a consequence, we run our measurements at temperatures as low as possible. A good measure of stability/lifetime is the ratio of active tracks obtained from 3D particles since active tracks are only considered from successfully tracked particles longer living than three time-steps. Thus, the lower this ratio becomes, the less stable the soap bubbles are. In fact, Figure 2 (right graph) exactly reveals this relationship between lifetime and mean temperature. The ratio of new tracks to active tracks may also be a measure for the lifetime, but also interruption of tracks, i.e. finished particle tracks may be retracked after several time-steps again and are treated as new tracks. As smaller the ratio as longer the lifetime and/or as lower the probability of interruption and retracking. Interruption may occur when light intensity fluctuations or overlay of particles in different depth of the volume take place and the algorithm cannot assign the particles continuously. But, those effects are interfering with actually new particles adding to the flow and hence it is not possible to conclude

in detail about the magnitude of each process. Thus, a systematic relation between active tracks and new tracks could not be found so far.

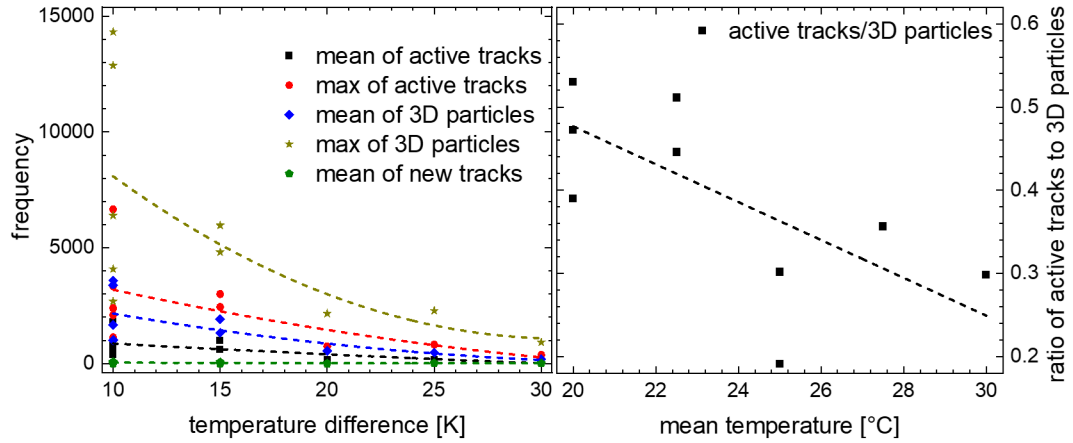


Fig. 2 Frequency of occurrence of active and new tracks as well as 3D particles as function of temperature difference between heating plate and cooling plate (left), and ratio of active tracks to 3D particles as function of mean temperature measured at the center of the RB cell (right). The fit curves (dashed lines) are only guides to the eye without physical meaning.

We also wish to evaluate the homogeneity of the particle distribution in the measurement volume. We calculate the probability density functions (PDF) for the three components of the velocity and the acceleration. Since our analysis has been undertaken for a confined turbulent flow, the PDFs should be symmetrically distributed around zero. Deviations may occur from the slightly reduced measurement volume with respect to the total volume of the RB cell or from local offsets induced by the continuous particle injection. We try to keep the latter effect as small as possible by optimizing the parameters of the bubble generator. More details on particle generation and measurement volume drawbacks may be found in (Loesch & du Puits, 2020, 2021). Figure 3 shows typical probability density functions of velocity and acceleration which are most-likely symmetrically distributed around zero.

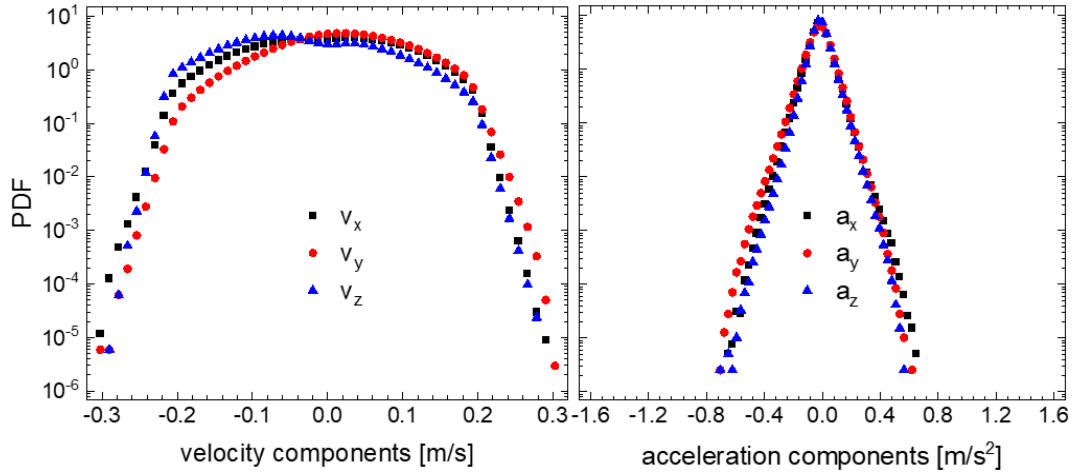


Fig. 3 Probability density functions of velocity (left) and acceleration (right).

All experiments show the same distribution of the velocity and acceleration components. Whereas the x-component of velocity is completely symmetric, the y-component is slightly skewed to positive values and the z-component is slightly skewed to negative values. Since this effect is found in all experiments, we assume a little systematic error in the calibration setup, but nevertheless, the results are accurate for the investigation of large scale coherent flow structures.

Finally, the reconstructed flow fields were inspected for large-scale coherent structures. Figure 4 shows one example of the Lagrangian field, where a coherent structure appears. The red circle marks the structure which closely resembles a dust devil-like vortex.

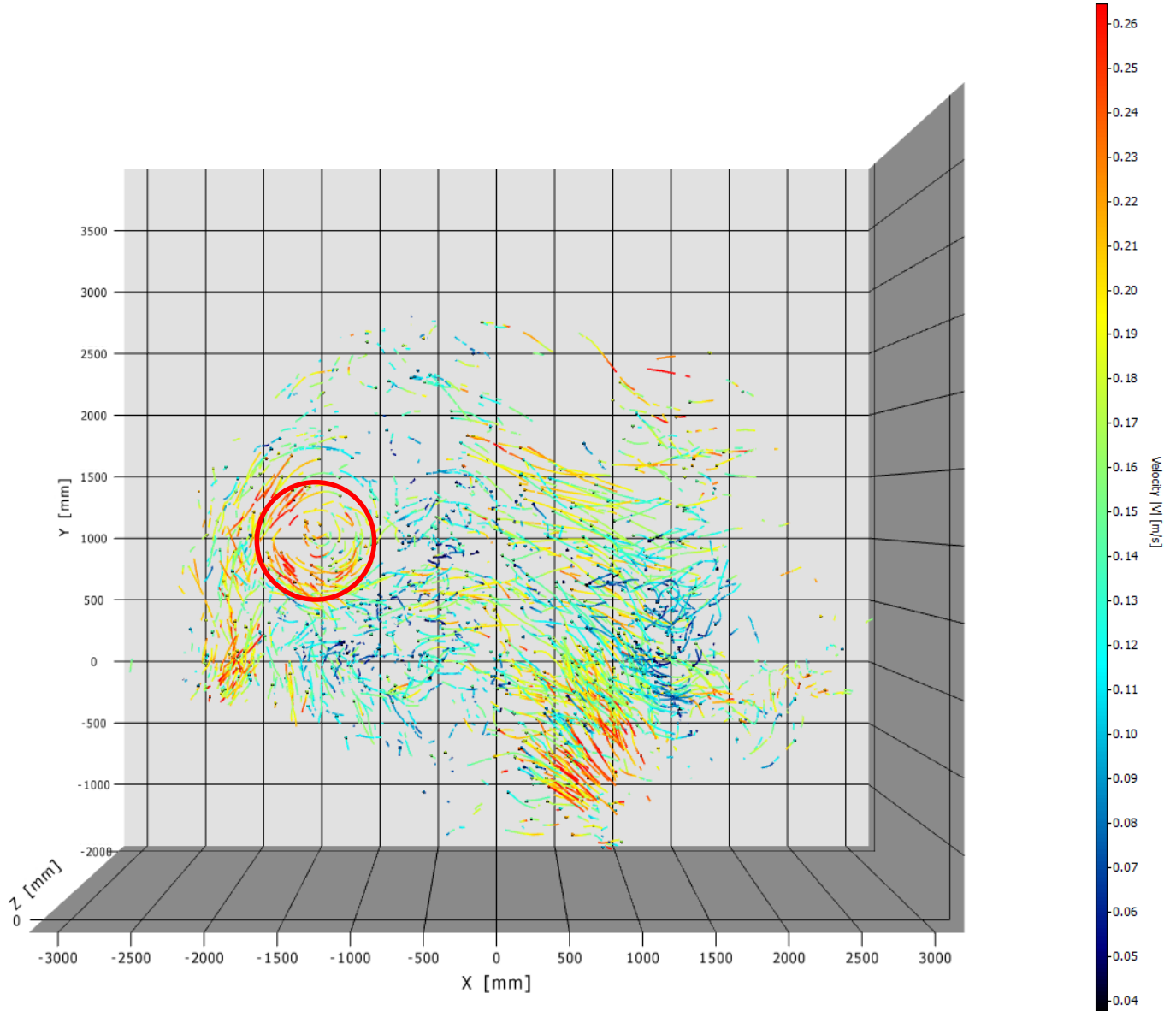


Fig. 4 Reconstructed Lagrangian velocity field at $Ra = 1.45 \times 10^{10}$ showing a dust devil-like vortex (red circle). Data was clipped to about half height of the convection cell ($0 \text{ mm} < z < 1250 \text{ mm}$) to emphasize the vortex.

In order to get a deeper insight into the vortex structure the Lagrangian flow field was transformed into an Eulerian one. Figure 5 shows the Eulerian field in horizontal planes of different height. In this case, also the data close to the heating plate ($z = 85 \text{ mm}$) reveals a vortex structure starting from there and continuing into the bulk where it starts to diminish at a height of about 1250 mm. The dust devil-like vortex has a diameter of about 1100 mm and a lifetime of about 18 s. The diameter of the vortex remains nearly constant over the complete height.

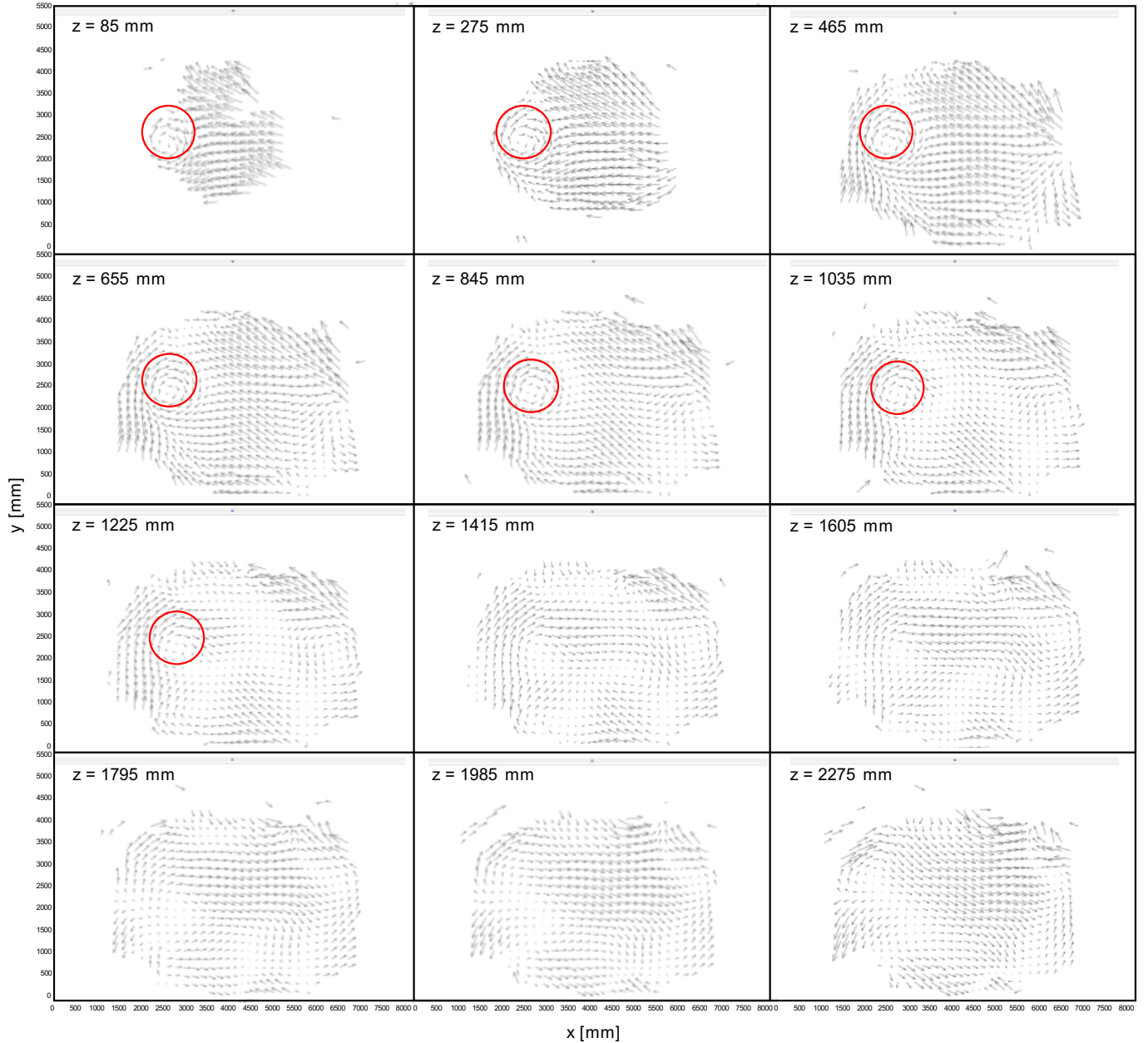


Fig. 5 Reconstruction of the Eulerian field and visualization of a dust devil-like vortex (red circle) starting at the heating plate and ending at a height of about 1250 mm.

For further characterization the vortex structure is exemplarily imaged for different time-steps in a mean height of $z = 655$ mm. The result is shown in Figure 6. At first the vortex starts to grow for about 6 s, preserves its size for about 8 s and then continuously decreases until it is completely diminished after about 19 s. During evolution the dust devil-like vortex is arbitrarily tumbling around in a circular region with a diameter of about 1400 mm, emphasized by the dashed black circles in the images.

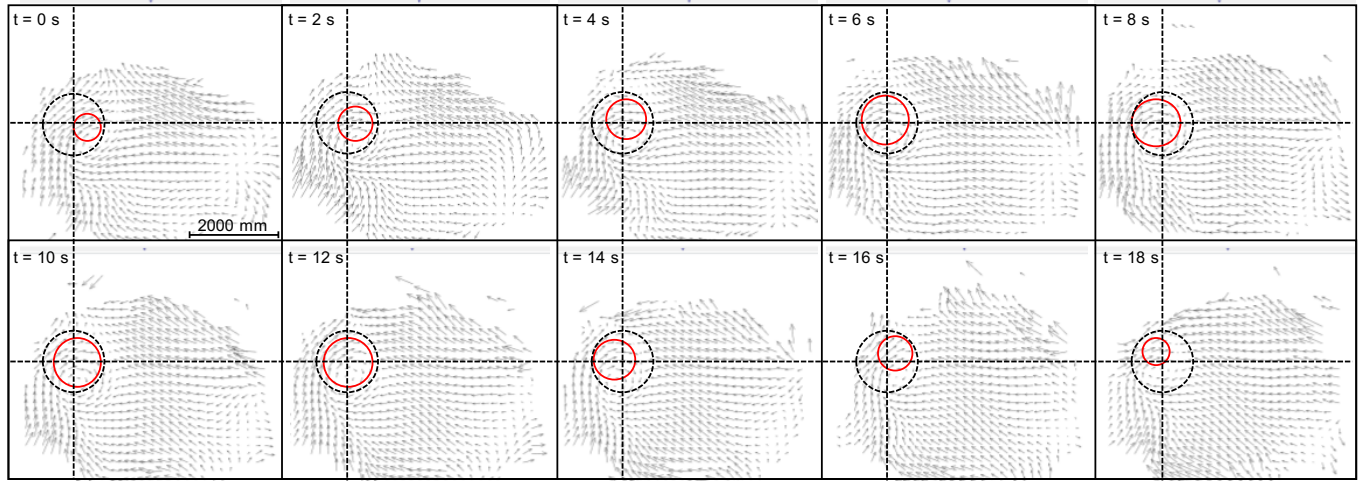


Fig. 6 Time-series of the dust devil-like vortex in a height of $z = 655$ mm. The red circle marks the dust devil-like vortex and the black dashed lines and circles emphasize the vortex tumbling around in a circular region with a diameter of about 1400 mm.

4. Conclusion

We show that large-scale coherent structures may be investigated in a very large Rayleigh-Bénard laboratory experiment by particle tracking velocimetry. It was the first-time experimental survey to simulate the genesis of dust devil-like vortices in an experiment modelling natural thermal convection. The experimental facility as well as the measurement setup have proven their suitability for investigation of large-scale coherent structures like dust devils in a laboratory experiment. The feasibility of the employed setup was discussed in detail at the example of a dust devil-like vortex that could be nicely resolved by particle tracking velocimetry and after converting the Lagrangian field into the Eulerian field. Although there are several experimental limitations, like e.g. that the volume of the convection cell cannot be fully resolved and particle seeding and lifetime could be optimized towards a higher and more homogeneous particle distribution, it could be demonstrated that the presented approach is a meaningful option to investigate flow phenomena covering up to 100 m^3 of volume, even though the smallest structures in the flow remain hidden.

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