

Large scale 3D Lagrangian particle tracking in mixed convection of realistic classroom settings

S. Weiss^{1,*}, D. Schanz¹, J. Lemarechal¹, J. Bosbach¹, T. Strübing¹, A. Schröder^{1,2}

1: Inst. of Aerodynamics and Flow Technology, German Aerospace Center (DLR) Germany

2: Chair of Image Based Measurement Techniques, Brandenburg University of Technology (BTU), Cottbus, Germany

*Corresponding author: andreas.schroeder@dlr.de

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ABSTRACT

We report Lagrangian particle tracking measurements in a realistic classroom setting to study the spread of airborne pathogens this environment. The setting consists of a $6\text{ m} \times 4 \times 2.8\text{ m}$ large room with transparent sidewalls and a transparent ceiling, in which chairs and desks were placed simulating an actual classroom. The influence of students was simulated by six realistic heated dummies sitting on the chairs at desks, of which one was additionally equipped with an artificial lung to simulate breathing. The room was seeded with about $700\text{ }\mu\text{m}$ large helium-filled soap bubbles and illuminated by a total of 2696 individual LEDs. Images were acquired using 8 streaming cameras with 65-megapixel sensors. With this setup we could track up to nearly 2 million individual particles for several minutes under different ventilation scenarios. These scenarios include the effect of open windows, the presence of a walking teacher in front of the classroom, or the presence of an active air filtration device.

1. Introduction

Aerosols are suspended particles small enough to be carried by airflow as passive tracers (Colbeck & Lazaridis, 2014). They play a crucial role not only in atmospheric chemistry, cloud formation or meteorology, but also serve as carriers for biological pathogens, such as viruses or bacteria. Examples include the common cold, influenza, tuberculosis, measles or corona virus disease (COVID). Such pathogens originate from the respiratory tract of an infected person, where they are expelled (e.g., by coughing or exhalation) while attached to small droplets. These droplets rapidly evaporate, leaving behind tiny infectious aerosols that can remain airborne for extended periods. In this airborne state, pathogenic aerosols are transported by the surrounding flow as passive tracers until they either decay, settle onto surfaces, or are inhaled by another person—potentially leading to new infections if the individual is susceptible. To estimate infection risks in enclosed spaces (Chen et al., 2021; Nordsiek et al., 2021) and design effective ventilation

systems that mitigate these risks (Schiepel et al., 2026), a detailed understanding of aerosol dynamics in realistic indoor environments is essential.

Since aerosols are small and as such follow the flow as passive tracers, the aerosol spreading can best be studied by measuring the velocity field. This needs to be done with rather high resolution in space and time because of the turbulent nature of mixed convection flows in typical indoor settings (Linden, 1999).

The best method for high resolution flow measurements is via Lagrangian particle tracking (LPT) (Schröder & Schanz, 2023). Here, the flow is seeded with small passive tracer particles that are recorded by multiple cameras, and their location, speed and accelerations are then calculated via triangulation. Efficient algorithms, such as *Shake-The-Box* (STB) (Schanz et al., 2013, 2016), allow precise tracking of more than a million particles. While for studying aerosol spreading, these Lagrangian information are important, with sufficiently dense seeding, also Eulerian velocity, acceleration and pressure fields can be calculated, by using proper interpolation techniques, such as FlowFit (Gesemann et al., 2016; Godbersen et al., 2024) or VIC+ (Schneiders & Scarano, 2016).

In this paper, we present flow field measurements in different realistic classroom settings, using STB to study the spread of airborne pathogens due to mixed turbulent convection. This work eventually should help to better model infection risks in winters or during the next pandemic.

Despite STB's established track record of over a decade, this study encountered unique measurement challenges, primarily due to the large measurement volume. The two main challenges were: (i) For sufficient spatial resolution, the room has to be seeded with a particle density that is of the order of $1/\eta^3$, with η being the Kolmogorov length. Due to the depth of view, a projection of these particles onto the two-dimensional chips would lead to such a strong overlapping of particle images that in fact it will be difficult to distinguish single particles. (ii) Due to the large lateral size of the room and limited distance available above the measurement room, wide angle lenses had to be used, with major lens distortion effects at the sides of the images.

2. Experimental setup

2.1. The classroom

The experimental setup is sketched in fig. 1. The flow takes place in a rectangular room that is 6 m long, 4 m wide and 2.8 m high. Its skeletal structure was made out of wooden beams, with transparent sidewalls (blue in fig. 1). Each sidewall was assembled from three sheets of 4 mm-thick, 2.8 m-long and 2.05 m-wide polycarbonate (PC). The sheets were attached at the top wooden frame and hung freely in order to avoid bending due to their own weight. Small gaps in between the polycarbonate sheets were covered with transparent tape, to prevent air exchange between the measurement volume and the laboratory.

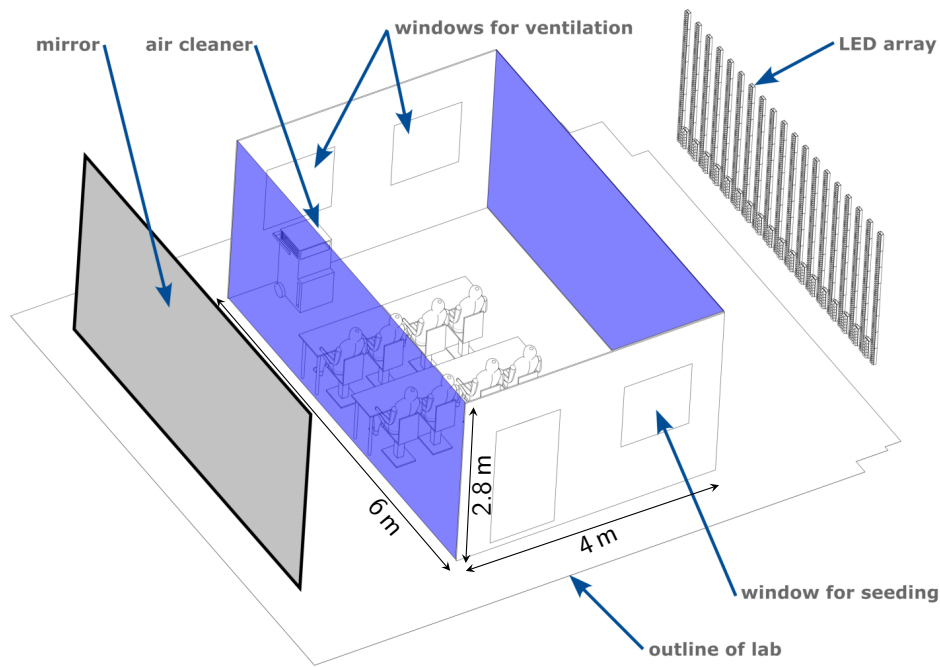


Figure 1. Outline of the experimental setup.

The measurement volume was sealed from the top with three PC sheets of dimensions $4\text{ m} \times 2.05\text{ m} \times 4\text{ mm}$. The sheets were clamped at the sides and supported by three steel cables, which were aligned in x-direction and mounted at the stone walls of the labs. The cables were covered in black rubber to minimize reflection and also tightened to straighten them as much as possible to reduce the bending of the sheets due to their own weight.

The front and back sides of the room were made of wooden boards. On the back side, two "windows" were installed while the front side had only one window as well as a "door". The doors and windows could be opened and closed if necessary to study natural ventilation scenarios. The single window at the front side was always open and was used to inject helium filled soap bubbles into the measurement volume (marked as HFSB in fig. 2).

All walls as well as the entire floor and any surfaces visible in the cameras were covered with black foil to minimize reflections. For the same reason we have also covered the ceiling with a black curtain (fig. 2(a)) as well as the floor outside the measurement area, and any piece of wall that was visible in any of the cameras.

Figure 3 shows an overview of the experimental setup.

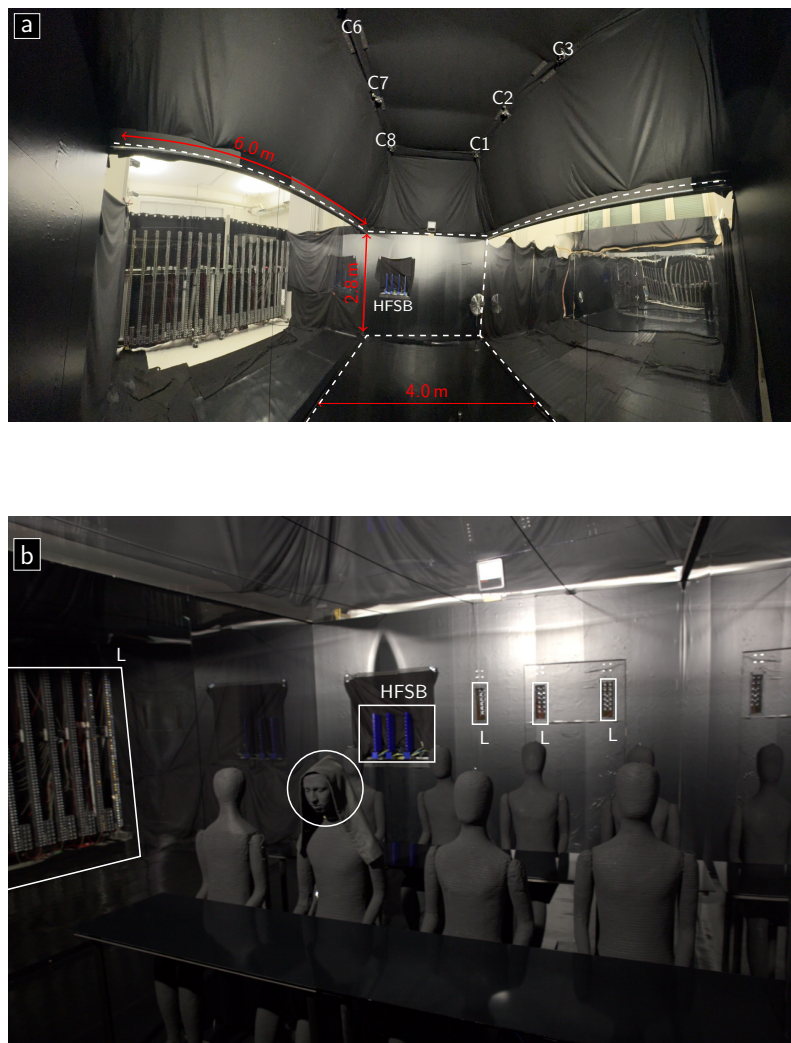


Figure 2. (a) Photo of the measurement volume taken with a fish-eye lens and without dummies. The image was taken without the top lid installed for better visibility. Dashed white lines mark the edges of the room as a guide to the eye. Camera positions at the top are marked with C1 . . . C8. Cameras C4 and C5 are not in the field of view. (b): Photo of the room with dummies. The white circle marks the dummies with an artificial lung. The rectangles mark the positions of the LED arrays (L) and the particle generator (HFSB).

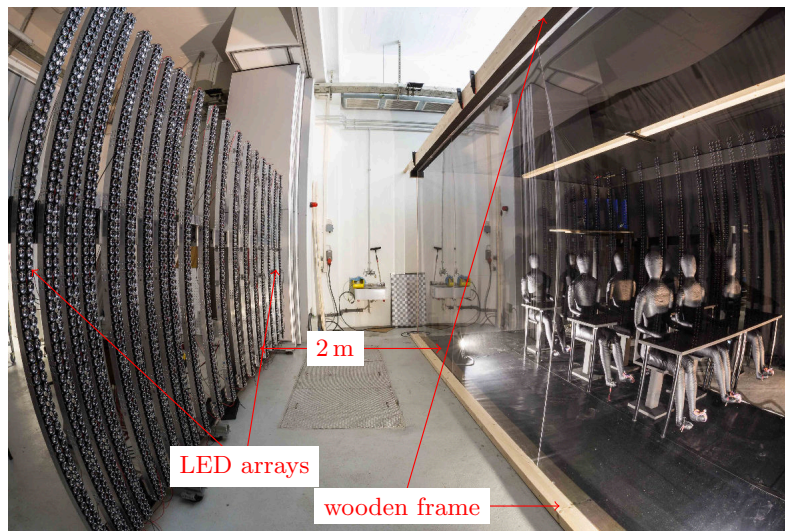


Figure 3. Overview of the experimental setting. On the left the LED arrays are shown. On the right side, the room is shown with heatable dummies inside.

2.2. Heated dummies

The goal of this project was to investigate how aerosols spread in a seminar room. There, in the absence of an active ventilation system, the main driver of the airflow is the buoyancy created by the persons inside. We mimicked such flows by placing appropriate life-size dummies into the classroom. The dummies were designed at the DLR in Göttingen (Lange et al., 2018) and have been used previously for measurements of only a single dummy Schröder et al. (2022). Out of the 8 dummies, one was equipped with an artificial lung ("L" in fig. 4b), which simulated breathing of a person (Kohl, 2020; Schröder et al., 2022). For this, the dummy had an open mouth with a hose connecting the mouth to an automated piston. The piston sucks and pushes air periodically and in this way makes the dummy inhaling and exhaling air from and into the room. In our experiment, the breathing amplitude was set to 0.6 litres air per cycle and the frequency to about 11 cycles per minute. This setting mimics the typical breathing patterns of a sitting person.

Each dummy was painted black with multiple layers of "Musou Black" (up to 99.4% light absorption), to minimize light reflection. Any surfaces that could not be painted, such as cables, electrical connectors or connectors of the artificial lung, were covered in black cloth. Each dummy was heated with a rate of 80 W, with heating starting about an hour prior to a measurement so that a stable temperature was achieved. The dummies were placed on black chairs behind black desks in two rows of four dummies each. The distance between neighboring dummies was about 60 – 70 cm and the distance between the front and back row was about 130 cm - 140 cm.

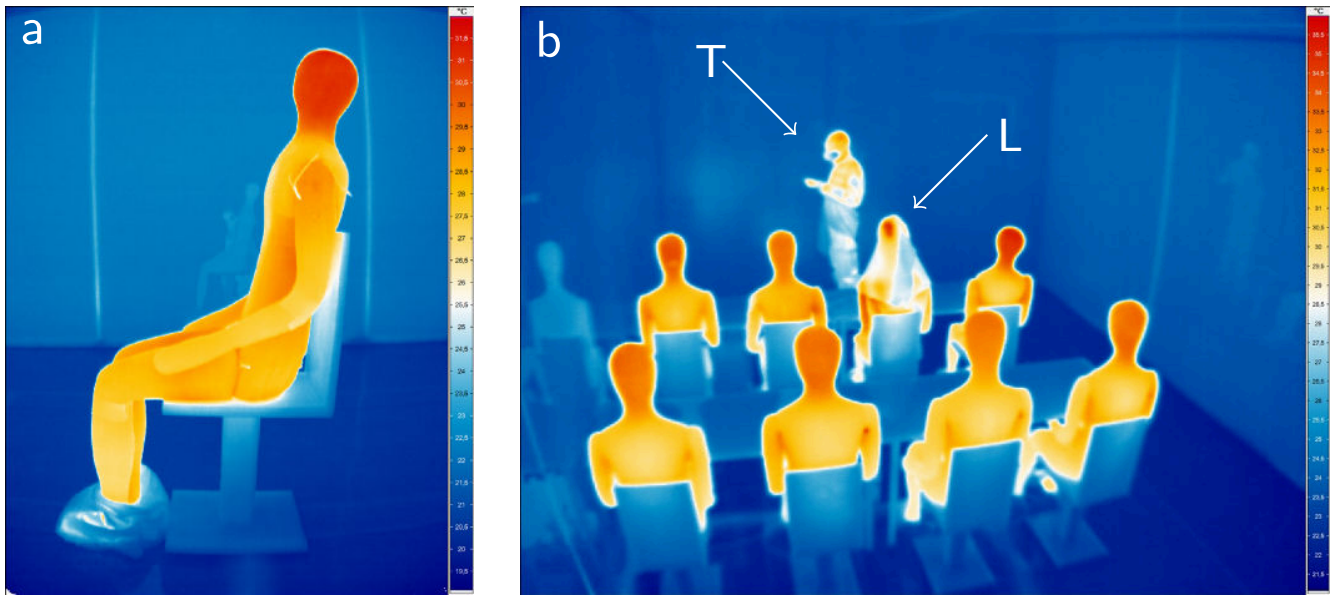


Figure 4. Infrared images of the heated dummies. (a): Side view of a single dummy. (b): View of the classroom with the 8 dummies and one teacher (T). One dummy is equipped with an artificial lung (L).

2.3. Illumination

For illumination we have used pulsed high power LEDs as shown in fig. 5. Each LED had a collimating lens attached to it in order to decrease its aperture. On one side of the experiment we installed 19 thin long LED arrays with each having 8×16 single LEDs (Luminus SST-40-WDS-F50-N4502, 20W/LED) as well as another set of 18×12 LEDs of a different kind (SFT-40-W65S-F50-N5652, 29W/LED) close to the bottom.

In order to avoid shadows from the dummies, three more arrays of 12 LED each (SFT-40-W65S-F50-N5652, 29W/LED) were installed at the front faces of the room (marked "L" in fig. 2(b)). In total, we illuminate the measurement volume with 2696 LEDs.

To avoid shadows from the dummies and hence to gain a more homogeneous illumination, light is reflected by a larger mirror wall on the opposite side of the measurement volume (see fig. 1 and fig. 2(a)). The LEDs were powered by ten power supplies (1x EA-PS 9080-100 1U). The LEDs were triggered with a function generator, which was set to a pulse width of about 15 ms and acquisition rates between 50 Hz and 70 Hz depending on the scenario investigated.

2.4. Tracer particles

Prior to a measurement, the flow was seed with nearly neutrally buoyant helium filled soap bubbles (HFSB), which were generated with a commercial bubble generator (by *LaVision*). The bubble

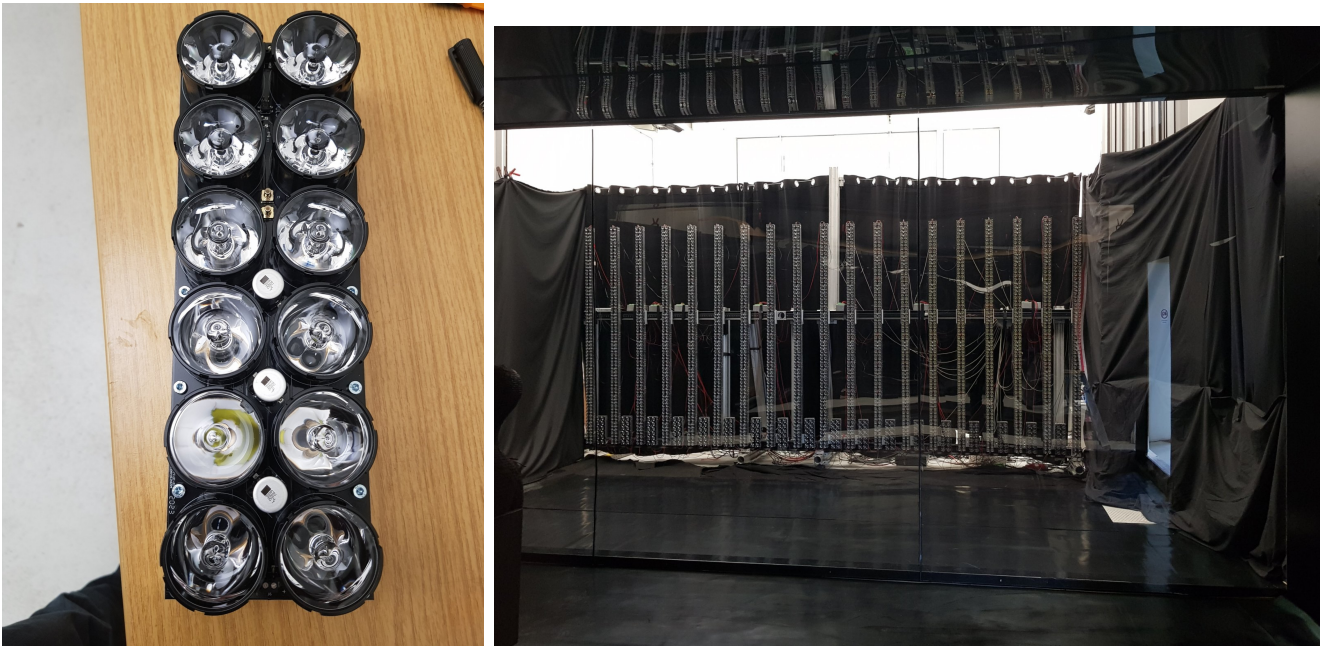


Figure 5. Left: LED segment consisting of 12 single LEDs. Such segments were used to illuminate the lower volume. Right: Image of all LED arrays for illumination.

had a size of about $(600\text{--}800)\mu\text{m}$ and were injected by four nozzle arrays with each having 10 single nozzles (marked HFSB in fig. 2b) through the window at the front side into the measurement volume. Compared to typical flow scales, the bubbles were small enough to be considered passive tracers. The room was seeded for about 2 to 3 minutes and the convection flow from the heated dummies was sufficient to homogeneously distribute the particles inside the room. The fan was switched off right after seeding and the flow was given sufficient time (at least 180 s) so that the added momentum from the HFSB-nozzle jets have decayed sufficiently, before a measurement was conducted.

2.5. Image acquisition and calibration

Images of the particle field were taken by eight streaming cameras (Emergent, HZ-65000-G-M, $9344\text{ px} \times 7000\text{ px}$, up to 70 fps) from different locations. The cameras had Scheimpflug-adapters attached to correct for the tilted viewing angles. Lenses of type Distagon T* 2.8/28mm were used to image a large field of view onto the 37.4 mm large sensor of the cameras. However, these lenses also exhibit significant image distortion further away from the optical axis, which has led to difficulties during calibration as will be discussed below.

The cameras were recording and streaming full images via fibre optics to a computer, on which they were saved directly on solid state disks (SSD). In order to reach full performance, four measurement computers were prepared, each having two independent SSD RAIDs. In this way, the

images from one camera were stored directly on one such raid. Cameras and LEDs were triggered simultaneously by a programmable pulse generator.

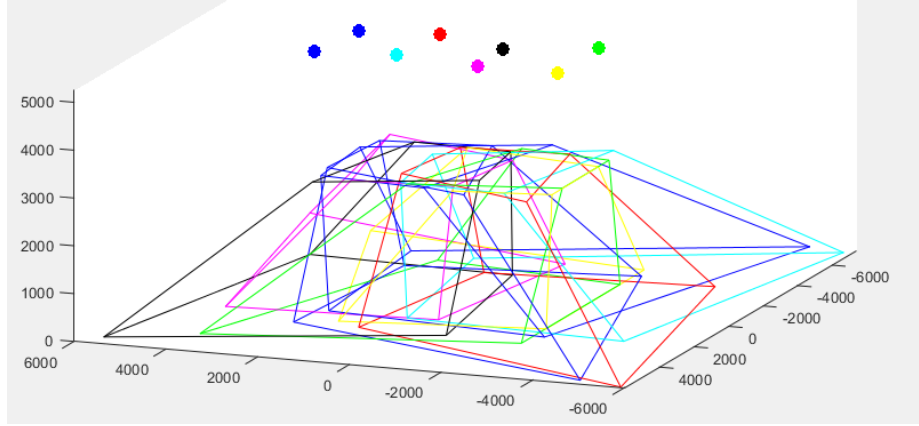


Figure 6. Field of view from the eight cameras.

The position of the particles as well as their velocities and accelerations were determined using our in-house *Shake-The-Box* algorithms (Schanz et al., 2013). In order to map the lab coordinate system (x, y, z) onto the eight camera coordinate systems (u, v) , we have fitted a two-plane model to the data points acquired using an appropriate calibration grid of known lattice constant (i.e., grid periodicity).

For calibrating a two-plane model, one usually uses calibration grids that span large parts of the field of view. This is even more important when short-focal length lenses are used with distortions far away from the optical axis. Since it is difficult to build an install calibration grids large enough for our measurement volume, we have used two $1.2\text{ m} \times 2.2\text{ m}$ large point grids with grid size 5 cm. Both grids were mounted onto an aluminum frame precisely leveled as well as aligned with each other using multiple line lasers in order to have one long grid of $1.2\text{ m} \times 4.4\text{ m}$. This grid was then placed at different horizontal positions, and images from all cameras were taken at each position, before the entire grid was moved to a new position. Images of the grid from one camera are shown in fig. 7. It took four different horizontal positions to cover the entire room for one vertical position. These images were then combined digitally resulting in an image of one large calibration grid as shown in fig. 7.

In this way, we calibrated two horizontal planes, a lower plane at $z = 39.1\text{ cm}$ (fig. 8) and a higher plane at $z = 177.0\text{ cm}$ (fig. 9).

The final calibration images (fig. 8 and 9) were evaluated using the DaVis-Software (by LaVision). DaVis does both, (i) the point recognition on the grid resulting in camera-to-world point correspondences and (ii) fitting the two-plane model.

The two-plane model with second-order correction turned out to be still insufficient to correctly map the lab-coordinate system onto the camera sensors, since optical distortions of the camera

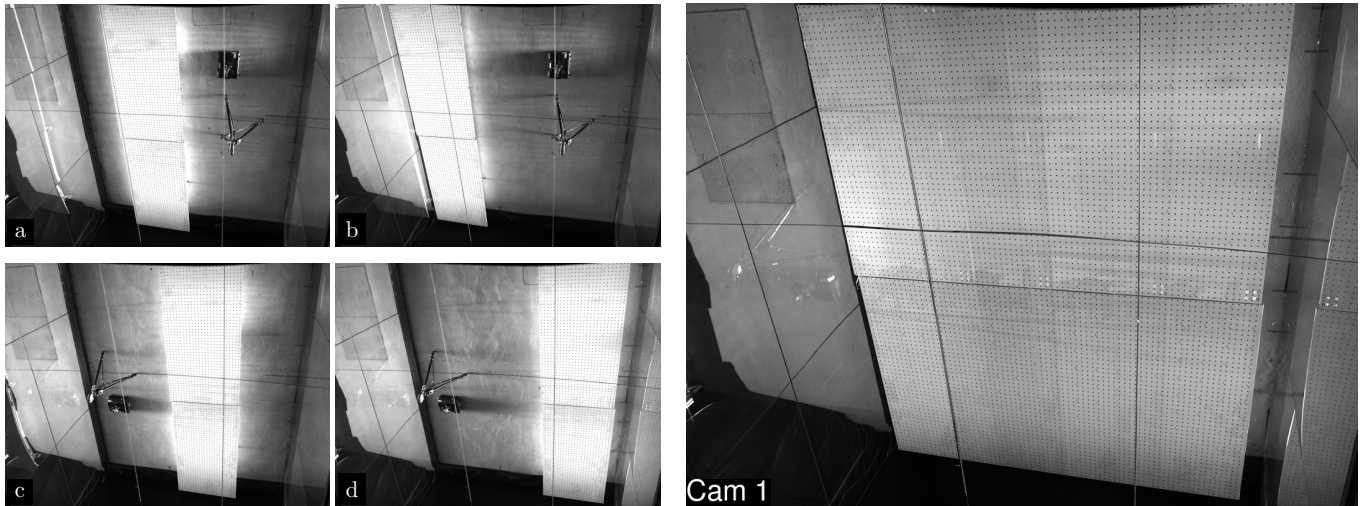


Figure 7. Snapshots of the calibration grid at different horizontal position as well as vertical positions $z = 39.1$ cm. The last image on the bottom right shows all nine previous images stitched together.

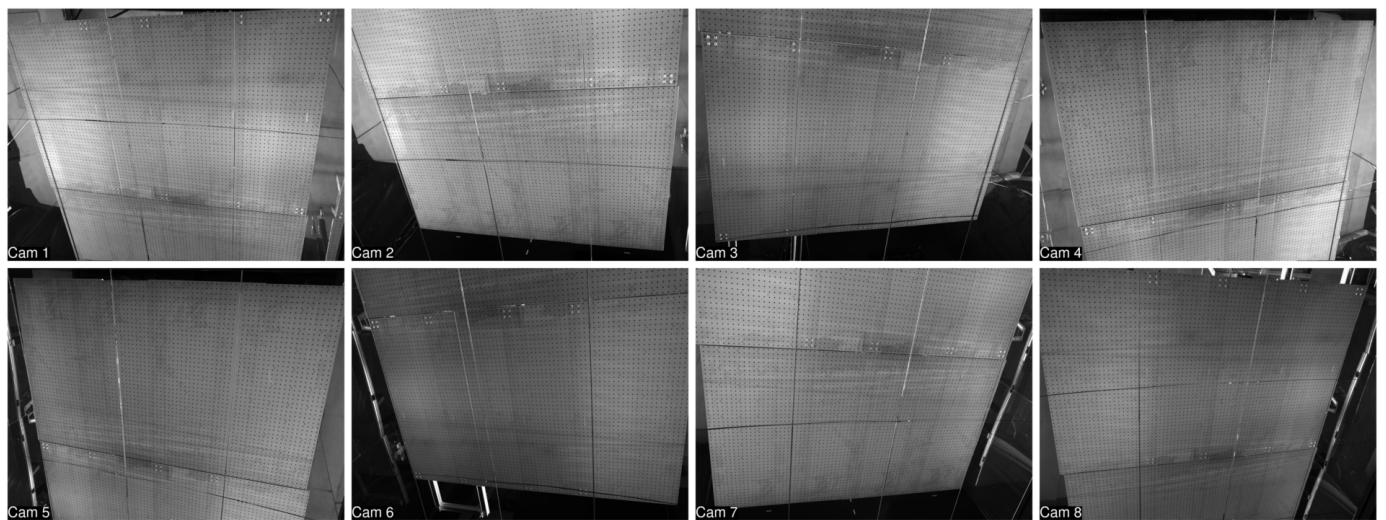


Figure 8. Final calibration image for each camera, created by stitching single snapshots together. The calibration grid was placed at $z = 39.1$ cm.

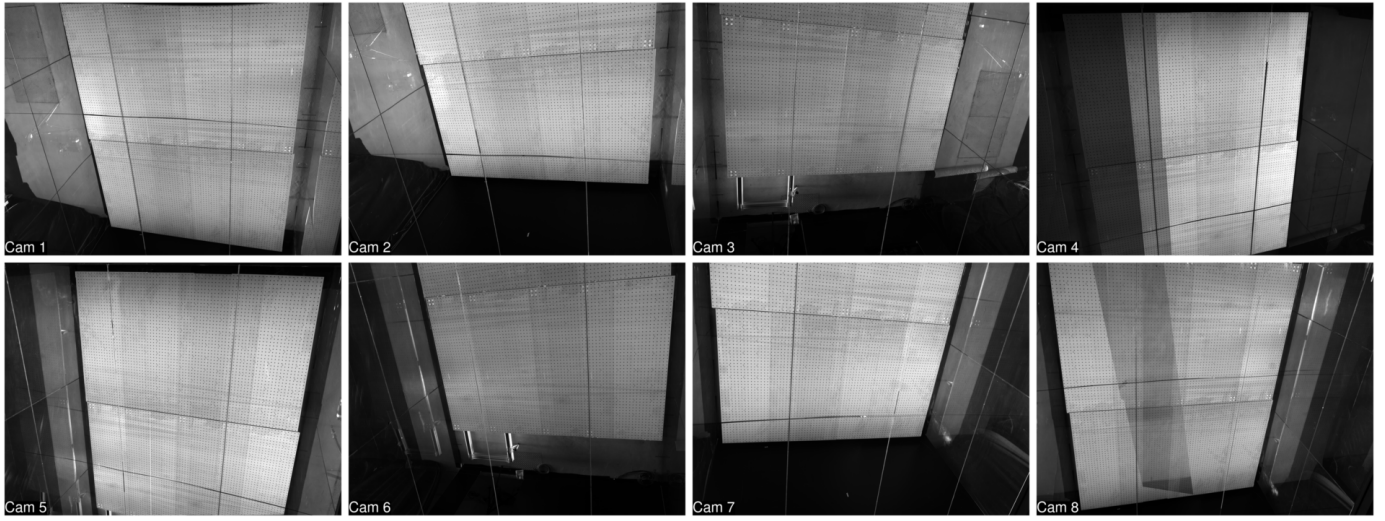


Figure 9. Final calibration image for each camera for vertical position $z = 177.0$ cm.

lenses were too large and even second order terms in the two-plane model could not account for that.

For a better quantification of the mismatch, i.e., the difference between the real projection of a location in the lab onto the camera and the calculated projection based on the two-plane model, we have made a measurement with very low seeding density. By using the two-plane calibration as well as allowing a large triangulation error for the *Iterative Particle Reconstruction* (IPR) step, particles could be identified and successfully tracked as long as they occurred at camera chip positions for which the calibration worked decently well.

Particles that were found in this way were back-projected onto the camera and the difference between this back-projection and the peak in the acquired image resulted in a shift-vector at this point. From all points detected two-dimensional shift fields (su, sv) were interpolated using b-splines. Such a shift field for one camera is shown in fig. 10. Clearly, these shift fields are function of the camera coordinates, i.e., $(su, sv) = \vec{f}(u, v)$. However, as it turned out, the shift fields (su, sv) seemed to also depend on the vertical coordinate z in space. While at this point we do not know the exact reason for this, we have calculated different shift fields for 17 vertical z -positions and interpolated the shift fields linearly for point in between.

This entire approach was done iteratively, meaning that the particle locations were detected from tracks using the calibration together with the shift field and a larger IPR triangulation radius. These data were then used to calculate another shift field, which was applied again to detect and track more particles. While the first iterations only allow for tracking particles, whose projections are not too far away from the center of the camera chip, with every iteration, the corrections improve and more particles were tracked further away from the image center, which helps to improve the correction more in these areas.

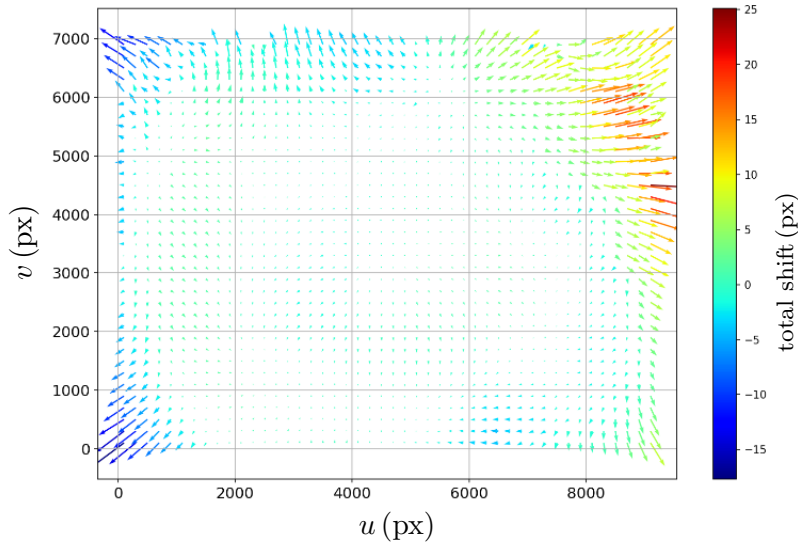


Figure 10. Calculated shift field for camera 3.

2.6. Curved epipolar lines

Due to the rather strong lens distortions, one also has to take into account that the epipolar lines, i.e., the projection of a straight line in space onto the camera chip, are no longer a straight line but curved. This needs to be taken into account while triangulating particles. In order to triangulate a particle in space, a single particle image is considered in one camera as shown for example for a single hypothetical particle in fig. 11(a). The location of the particle image in one camera together with the calibration function provides information about two of the spatial coordinates of the physical particle. For the third spatial coordinate, however, images of the same particle need to be found in the other cameras. For this the line of sight (a line connecting the particle and the camera) is projected onto the other cameras and particle images close to this line are evaluated as potential candidates. In the case of negligible lens distortion, the projections of these straight lines-of-sight are straight lines as well. However, in our case the far field camera lenses create significant distortions of the image close to its edges, the projection is no longer straight but rather curved. This is known already for a long time Zhang (1996), but since the curvature is usually small, it has been neglected in previous measurements.

To illustrate this, we show in fig. 11(a) the image of a hypothetical particle as it is seen from camera 1. The real particle can be anywhere in physical space along a line, which is bound by the ends of the measurement volume, whose projections on camera 3 are shown as red dots in fig. 11(b). The real epipolar line (the projection of the line-of-sight) is not just the straight line connecting the red dots but is curved due to lens distortions, as can be seen in fig. 11(c), where scale of the x-axis has been enlarged. While the deviations between the straight line (blue) and the real epipolar line (red) in fig. 11(c) in this example is only a few pixels, for particles close to one side of the camera

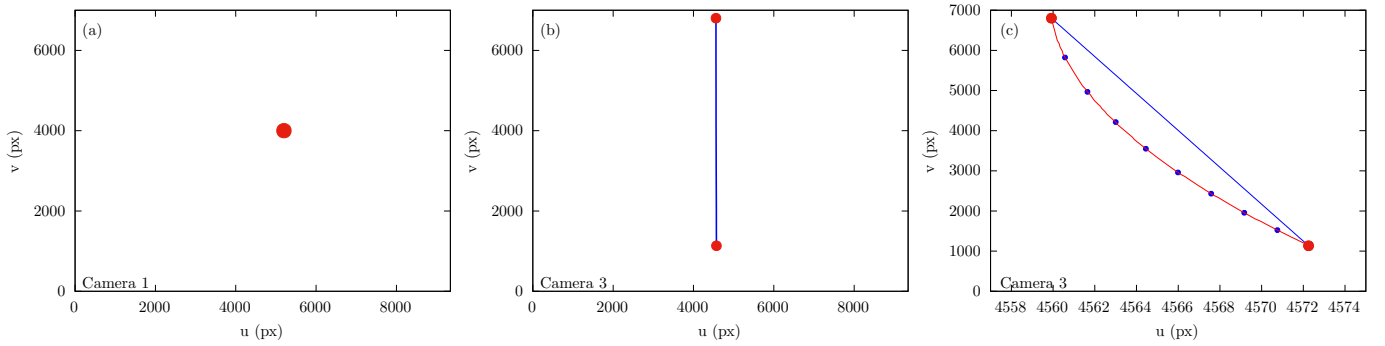


Figure 11. (a) Position of the image of a hypothetical particle as seen in camera 1, can be due to a particle that is anywhere along a straight line in real space. This line is of course bound by the measurement volume, i.e., the line of sight. A projection of line of sight onto camera 3 is shown in (b). The red dots mark the bounds due to the measurement volume. (c) shows the projected line with an enlarged x-axis. The red line marks the projection. The blue line is just a straight connection between the end points.

sensor, deviations can be up to 30 px.

In order to account for the curvature, we evaluated the projection of line of sight at two endpoints of a camera as well as $n=8$ points in between (blue dots in fig. 11c). The projection of these n points are then connected via linear interpolation.

3. Results

3.1. General flow structure

Figure 12(a) shows a snapshot of the velocity vectors of the particle field from one investigated scenarios with just 8 heated dummies. Here, each particle is color coded with its vertical velocity w . In total we could track up to 1.9×10^6 particles for this case. The image illustrates the large volume that can be investigated, which expands the entire room, except the regions close to the entrance, i.e., the regions close to the wall behind the dummies, which were not covered by the cameras.

For a better visualization of the flow structure close to the heated dummies, we show in the left plot of fig. 12 only particles that are in half of the room. In this plot the strong updraft regions (red) above the heated dummies become clearly visible. Hence, above the dummies warm fluid rises until the top, where it is deflected towards the sides. The fluid then sinks back towards the bottom close to the front wall, where negative vertical velocity is depicted in blue in fig. 12.

The strong updraft regions above the dummies are also neatly seen in fig. 12(b), which shows a view of the particle cloud from above. Here, the locations of the dummies are visible as red areas, where the warm plumes reach the top plate. Interestingly, in between the warm plumes rather

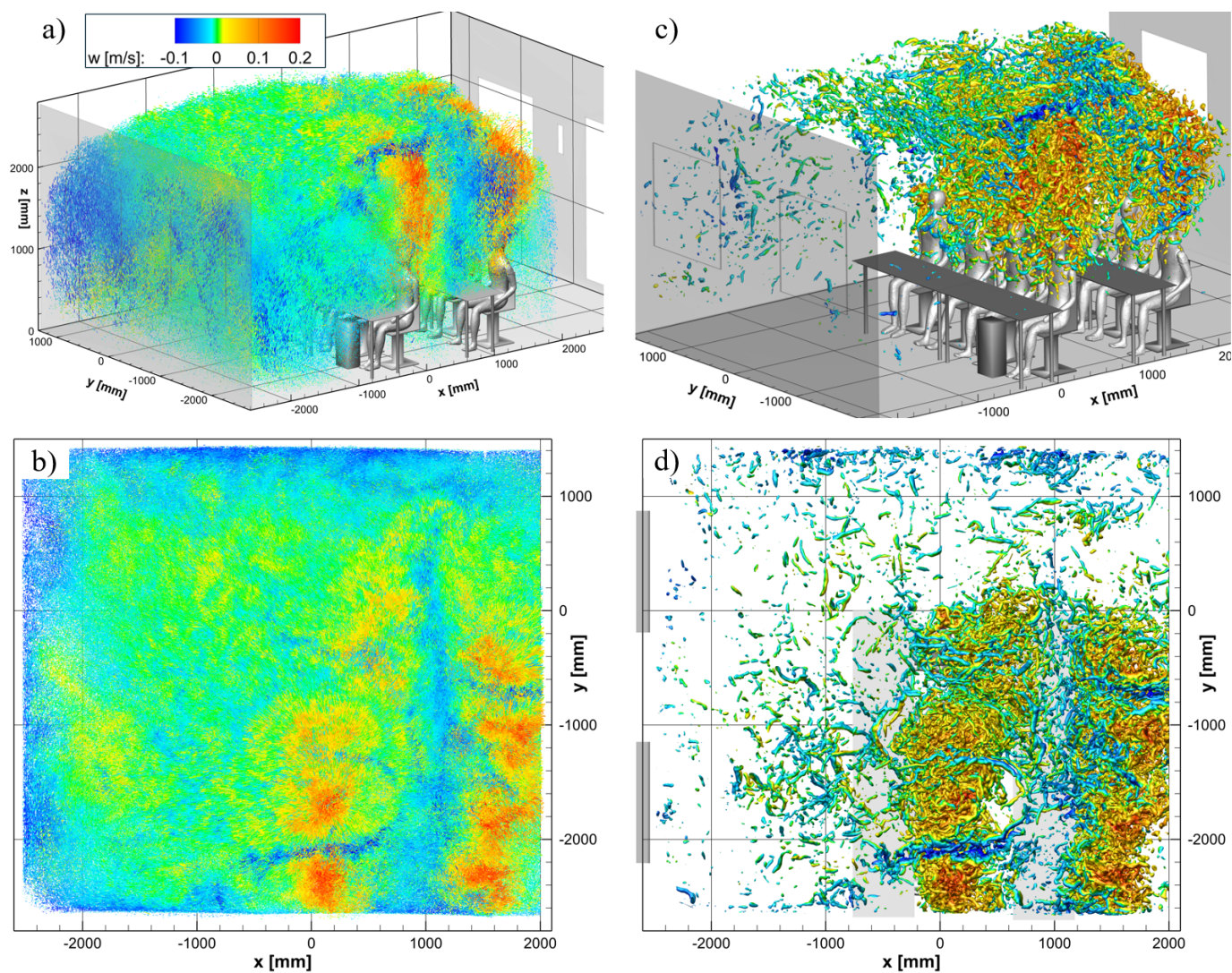


Figure 12. Velocity vectors of about 2×10^6 particles, color coded with their vertical velocities, seen from the side (a) and the top (b). Isosurfaces of the Q -value ($Q = 1 \text{ s}^{-1}$) with the same color coding, seen from the side (c) and the top (d).

thin regions are visible with negative velocity that are located right between the dummies. This suggests the existence of rather narrow circulation regions, in which fluid rises due to buoyancy just above a dummy, but also sinks back in the region between neighboring dummies.

Such small recirculation regions are particularly interesting regarding the transmission of airborne pathogens. From a practical perspective, these flow structures suggest that short plastic sheets, which were frequently being used during the last COVID-19 pandemic to avoid infections over small distances, are rather inefficient in unventilated rooms, since the aerosol particles rise to the top of the room anyways. Furthermore, it is hence expected that viral spread is slower in these scenarios compared to a case where a large scale circulation roll is present that spanned over the entire room.

Besides the regions between dummies, fluid predominantly sinks very close to the walls, where the warm fluid is cooled down back to room temperature by the sidewalls, which here act as the only heat sink.

From the particle tracks, we have also calculated Eulerian fields of the velocity, acceleration and pressure using FlowFit3 Godbersen et al. (2024), which in turn are used to calculate subsequent properties, such as vorticity and Q-value. Isosurfaces for $Q=1\text{ s}^{-1}$ as seen from the side as well as from the top are plotted in fig. 12(c) and (d). The color represent, again, the vertical velocity. One sees that most vortices occur in the updraft regions above the dummies, where plumes rise towards the ceiling. It is to no surprise that vortex density is much smaller in front of the dummies, where no heat source or sinks accelerates the fluid.

3.2. Particle displacement

One of the most relevant Lagrangian properties in turbulence research as well as for the study of viral spreading is particle displacement. It measures, how far on average particles are carried by the turbulent flow field in a given time τ .

We consider the displacement for all three spatial coordinates separately. While under isotropic and homogeneous conditions, these are the same, this might not be the case here. In fact our flow is mainly driven by buoyancy and therefore is not isotropic and due to the small size of the room and the dummies in it, it also cannot be considered homogeneous on larger scales. The displacement for a single coordinate " i " is defined as

$$\Delta_i^2(\tau) = \langle (x_i(t+\tau) - x_i(t))^2 \rangle_{t,p},$$

where the average $\langle \rangle_{t,p}$ is taken over all particle tracks and all times. The result is plotted in fig. 13. The green diamonds mark the displacement in vertical direction Δ_z . It shows typical features of particle displacement in turbulent flows, such as a ballistic regime for small τ , with $\Delta_z^2 \propto \tau^2$ and a diffusive regime $\Delta_z^2 \propto \tau$ for larger τ . The diffusive regime becomes dominant at time scales above

which correlation is lost. Hence, on larger time scales, the particle can be considered a random walker. The cross-over from the ballistic to the diffusive regime happens after about 5 s as can be seen in fig. 13, which marks the typical correlation time scale..

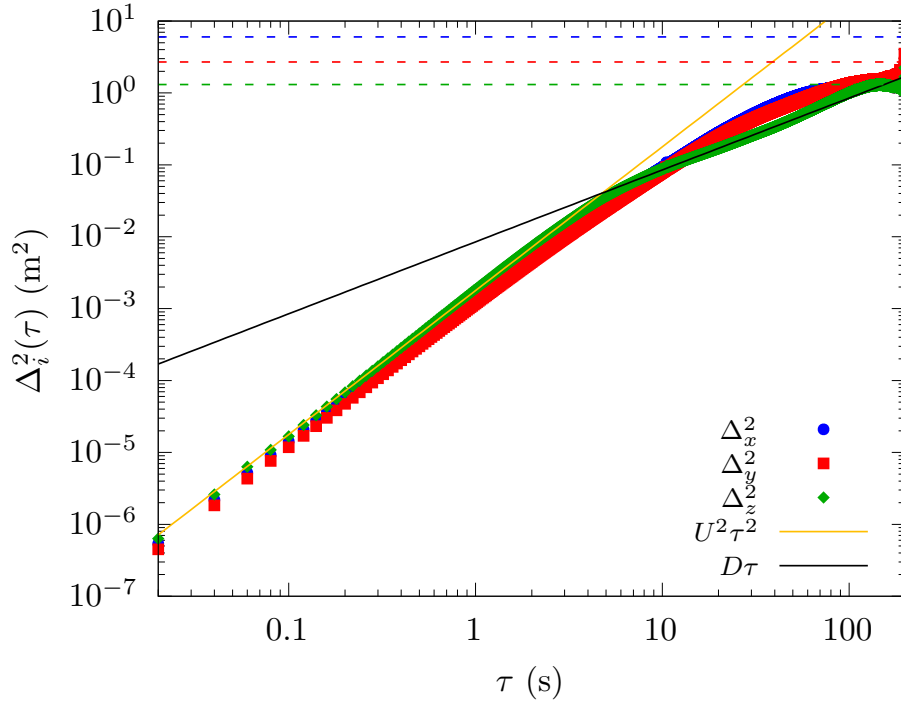


Figure 13. Square displacement averaged over all tracks in the room. Different colors mark different components (see legends). Solid lines mark fits to the ballistic and the diffusive regime. Dashed lines mark the maximal expected displacement $\Delta_{x,\infty}^2$ (dashed blue), $\Delta_{y,\infty}^2$ (dashed red) and $\Delta_{z,\infty}^2$ (dashed green).

Due to the finite measurement volume the displacement cannot become arbitrary large. In vertical (z -) direction the room is only 2.8 m high and therefore longer displacements are impossible and the curves have to saturate for sufficiently long times. In fact, this saturation does not happen at $\Delta_z^2 = (2.8\text{ m})^2$, but at smaller values which can be computed via the average squared distance between any coordinates, i.e.,

$$\Delta_{z,\infty}^2 = \frac{1}{H^2} \int_0^H \int_0^H (z_1 - z_2)^2 dz_1 dz_2 = 1.31 \quad \text{with} \quad H = 2.8\text{ m}. \quad (1)$$

While in fact, over short times as well as for single tracks the covered distance can be larger (as large as H^2), as an average over many particles and over times, after which correlation is lost, the plots are expected to settle at Δ_∞^2 if just the measurement time is long enough. Similarly, we can also calculate maximal mean displacements in x - and y -direction as $\Delta_{x,\infty}^2 = 4.17$ and $\Delta_{y,\infty}^2 = 2.67$ m. Note that the maximal distance in x -direction is not the room length, but the length of the observable volume (5 m). We have plotted Δ_∞^2 as dashed lines in fig. 13, and see that indeed, Δ_z^2 approach $\Delta_{z,\infty}^2$ for very large τ .

component	U (m/s)	D (m ² /s)
x	0.037 ± 0.002	$0.017 \pm 3 \times 10^{-5}$
y	0.033 ± 0.002	$0.014 \pm 2 \times 10^{-5}$
z	0.042 ± 0.002	$8.476 \times 10^{-3} \pm 3 \times 10^{-6}$

Table 1. Fit parameters for the curves in fig. 13.

The data for the two horizontal displacements $\Delta_{x,y}^2$ show a similar behaviour as Δ_z^2 . Both show a clear ballistic regime at small τ , which changes above $\tau \lesssim 5$ s to a regime with a much smaller slope. However, the transition to the diffusive regime is less sharp and hence a diffusive behaviour with a power law $\Delta^2 \propto \tau$ is only visible over a rather small τ -range.

Furthermore, in the ballistic regime, the red squares and blue bullets are slightly lower than the green diamonds, reflecting lower velocities. This comes as no surprise given that buoyancy acts in vertical direction. A quantitative value for the velocity can be gained from fits to the data in the ballistic regime to a function $\Delta_i^2 = U_i^2 \tau^2$. The results are listed in table 1. There, we see that not only is U_z larger than the other two, but also is U_x larger than U_y . This is because, on the largest scales the flow is predominantly aligned in the x-direction. While this is already visible in fig. 12, it will be seen more clearly below in fig. 14.

Although the diffusive regime is less clearly visible for Δ_x^2 and Δ_y^2 , we still fit a function $\Delta_i^2 = D_i \tau$ to the data to gain a quantitative measure for the diffusion rate D_i . At a first glance it is a bit surprising to see that the diffusion rate is smallest in z-direction and largest in x-direction. Unfortunately, at this point, we don't have a very good explanation for this. It might be that due to the large scale flow structure vertical momentum is quickly converted into horizontal momentum and hence once a particle has left the smallest eddies on which the flow is correlated, it is trapped in eddies with a predominantly horizontal motion.

While average particle displacement is interesting to get an overview of the dominant flow direction in the flow or other global features, if one is interested in infection dynamics of a closed room, particle displacement from one dummy to another is more relevant. For this, we consider tracks that were exhaled from the dummies. To do so, we define a sphere with a radius of 10 cm around a dummy's "mouth" and select only particles that have been within this sphere at some point in time. We then cut the part of the tracks before the particle has entered the sphere and only consider the track at later times.

Figure 14 shows about 500 tracks that were exhaled from one specific dummy (front row, second from the right). The tracks do not belong to particles that were exhaled at the same time, but at different times and the color represents the time duration from the initial release. It is clearly seen that due to the strong updraft generated by the air heated by the dummies, particles first rise straight to the ceiling, where they are deflected predominantly toward the front. Most particles move along

the ceiling to the front side of the room, before they sink down. However, most particles do not descend all the way to the floor but only rather close to half-height or so, before they are transported back to the sitting dummies. This suggests that a large-scale circulation roll exists in the front part of the room that only covers the top half of the room, i.e., the space above the tables.

Looking from above (fig. 14b) it becomes clear that indeed the flow is aligned predominantly in x-direction. Particle transport in y-direction is slower and rather symmetric, i.e., roughly the same amount of particles are transported to the left (negative y-direction) and to the right (positive y-direction).

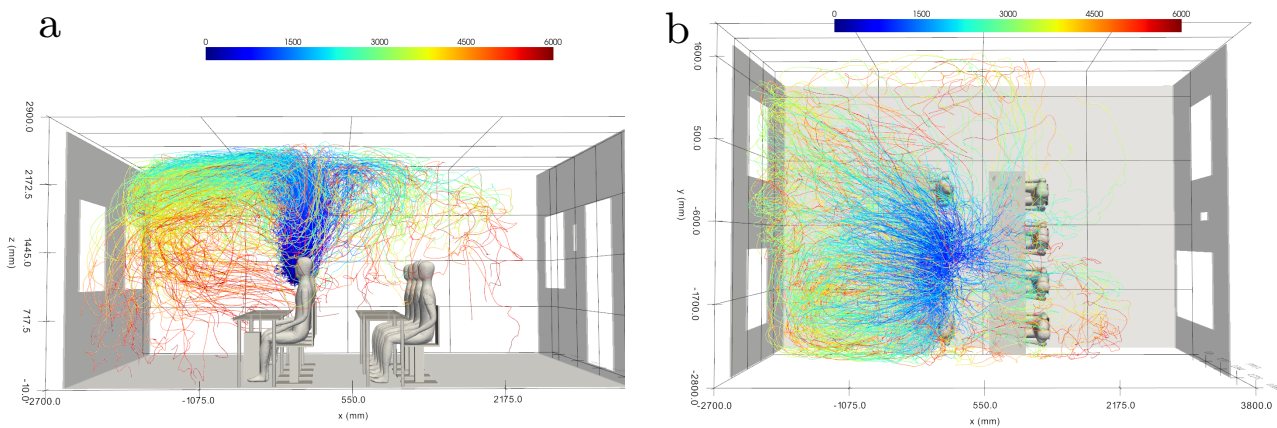


Figure 14. Visualisation of the tracks of 1000 particles that have been "released" from a specific dummy at some point in time. Different particles were released at different times, and the color code represents the time duration measured from the time a particle left the mouth (the area close to it). (a) shows a view from the side, while (b) shows a view from the top.

We would like to note that the dummy considered here was the dummy with the artificial lung. While a subtle influence of breathing on the particle trajectories is visible upon close inspection, over longer time and length scales, the flow from the lung is negligible compared to the buoyant flow generated by the heated dummies.

In fig. 14 shows the tracks from one single dummy. How do tracks from different dummies look like and how is the interaction between the flow structures above different dummies? To answer these questions, we plot in fig. 15 tracks from particles that were "released" from different dummies. In blue, we show tracks emitted from the same dummy as in fig. 14, whereas we only plot half of the tracks. For comparison, we show in red tracks from particles exhaled from a dummy sitting right behind (fig. 15 a and b) and in the front row at the very left (fig. 15 c and d).

Examining the particle tracks from the dummy sitting right behind each other (fig. 15 a and b) shows that the large scale convection rolls driven by the dummies' buoyancy are well separated from each other. While one circulation reaches from the front dummy until the front end of the

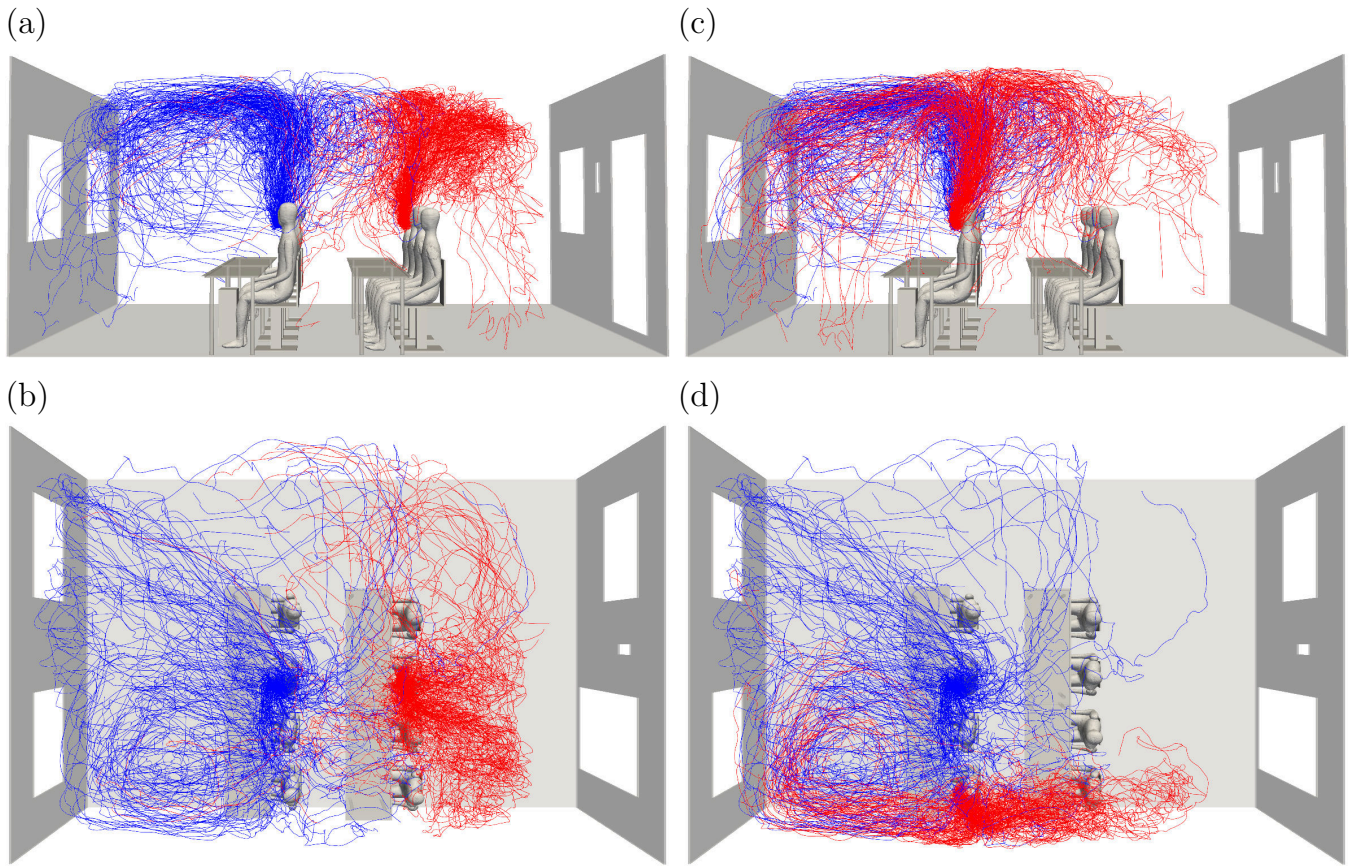


Figure 15. Comparison of the tracks exhaled by different dummies. Blue are tracks due particles exhaled from the dummy with the lung, i.e, the same as in fig. 14. Red tracks are from particles exhaled by the dummy one row behind (a and b), or the one two seats to the left (c and d). (a) and (c) show the side view. (b) and (d) show the tracks as seen from the top.

room, the dummy behind initiates a circulation towards the back of the room. We note that the entire circulation can not be seen because the field of view does not cover the regions close to the back of the room.

The situation is rather different for the dummy sitting in the front row at the very left (red in fig. 15c and d). Particles "exhaled" from its mouth are also transported first towards the ceiling, but there, while some particles are transported towards the front of the room, a significant amount is also transported towards the back and are even sucked in to the downwards flow right in front of the person right behind. This observation highlights how the presence of a side wall influences the large scale circulation structure. In this particularly case we would expect the person sitting in the second row close to the left wall to have a higher infection risk as person sitting at a different seat in the second row.

4. Conclusions

In conclusion, here we report on *Shake-The-Box* Lagrangian particle tracking measurements to investigate aerosol dispersion in a typical classroom setting under laboratory conditions. Using eight streaming cameras, large arrays of more than two thousand single LEDs, we were able to track nearly 2 million particles. With this, we could measure large scale flow structures which are driven by buoyancy from heated dummies in the room. We found that the size of convection rolls is controlled by the seating pattern of the dummies (persons) in the room as well as the height of the tables. Every person create their own convection roll, rather than all dummies contribute to one large circulation spanning the entire room. However, due to turbulent mixing, trajectories of particles stemming from individual starting points eventually distribute homogeneously over the entire volume. The dispersion and path of particle clouds do depend on the local starting point and potential transmission from one person to any other can be investigated with the long time series of the present LPT dataset. Aerosol spreading under different ventilation scenarios has also been investigated using the same technique and the results will be published elsewhere.

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