Direct Numerical Simulation of a cough-induced aerosol-laden turbulent jet interacting with a large-scale circulation

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Background

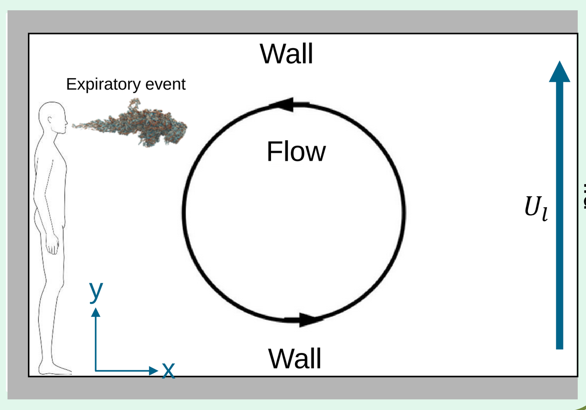
Research on respiratory aerosol transmission of pathogens has gained dramatic interest since the beginning of the COVID-19 pandemic. It is well known that ventilation has a significant impact on the spread of aerosols which are transported by the air over long distances due to the environmental airflow. In this context, a better understanding of the mechanisms of virus spread in ventilated indoor environment is necessary.

Objectives

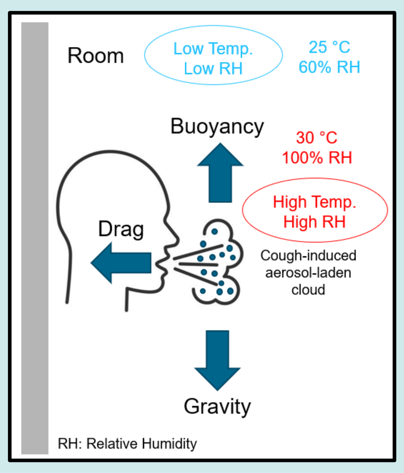
The dispersion of cough-induced particle clouds under the influence of a large-scale circulation (LSC) is studied using direct numerical simulations (DNS). Extending our previous research on droplet dispersion in unventilated environments [1], this study focuses on aerosols within a turbulent cough-generated flow and their interaction with a LSC. Horizontal advancements of the particles are analysed using centroid and dynamic time warping (DTW) methods.

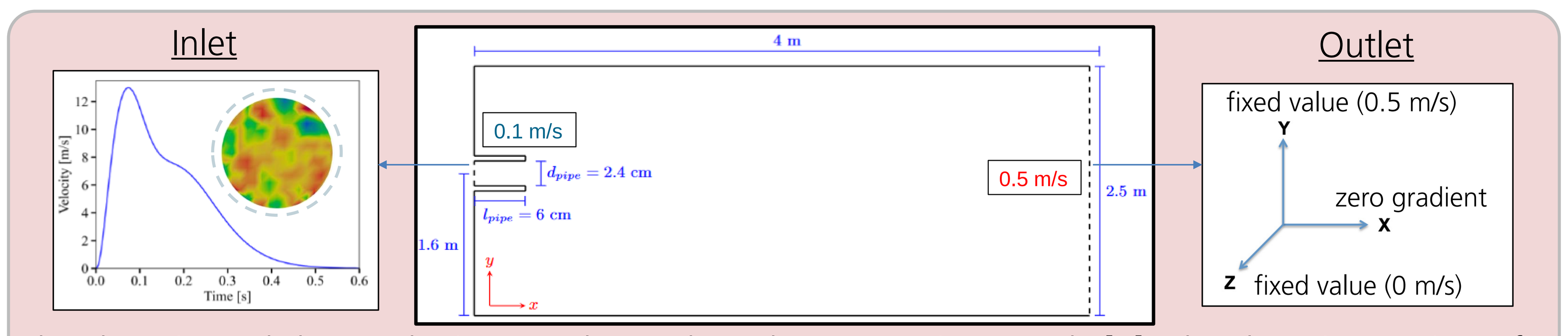
Methods

Cabin environments and rooms are often characterised by LSC. A DNS of a lid-driven cavity flow was performed using a semi-implicit time integration scheme to obtain an initial flow field for the DNS of the particle jet. The flow is driven by the lid at the boundary downstream of the jet, so that the induced large-scale circulation moves downward near the mouth opening.



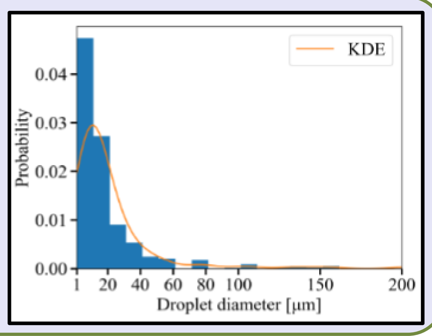
The DNS of the particle jet interacting with a LSC is performed using a second-order accurate finite-volume method in combination with a projection method [2] for the velocity-pressure coupling and an explicit, second-order accurate Euler-Leapfrog time stepping. The transport equations for the temperature and vapor concentration are coupled to the momentum equations using the Boussinesq approximation to include the buoyancy effect.



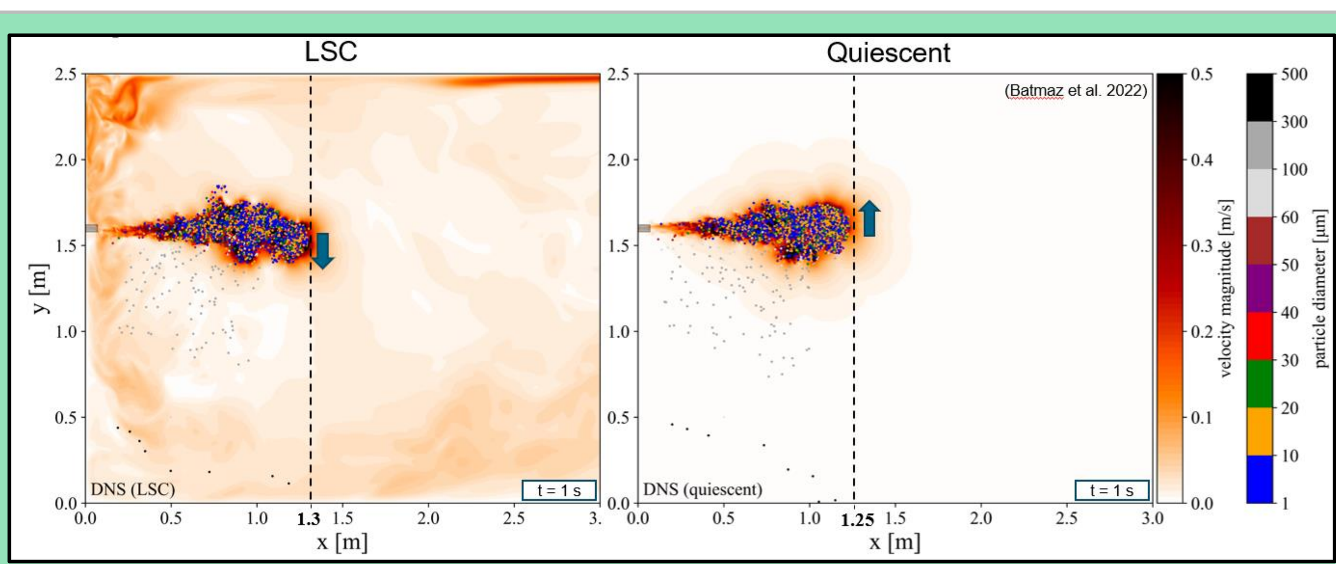


The domain and the mesh size are chosen based on a previous study [3]. The domain consists of a rectangular and a circular smooth pipe, representing the simplified room and the mouth opening, respectively. Eddy-like disturbances [4] are added to the mean velocity [5] of the cough at the inlet to initiate the turbulent jet. A direction-mixed boundary condition is applied at the outlet, providing a fixed velocity in the tangential directions and a zero gradient velocity in the normal direction.

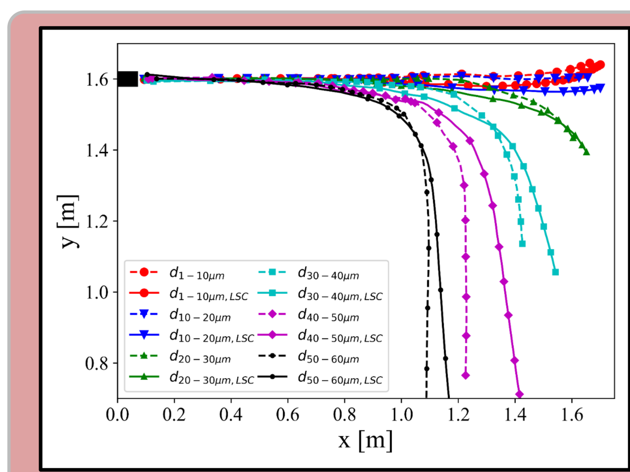
The exhaled particles are assumed to be spherical points with constant mass and are tracked using a Lagrangian approach considering the drag and gravitational forces. The DNS is initialised with 2500 particles positioned at rest with a initial size distribution [6] shown in the figure. Particles smaller than 60 µm are categorized by size for further analysis using centroid and dynamic time warping (DTW) methods in the horizontal direction.



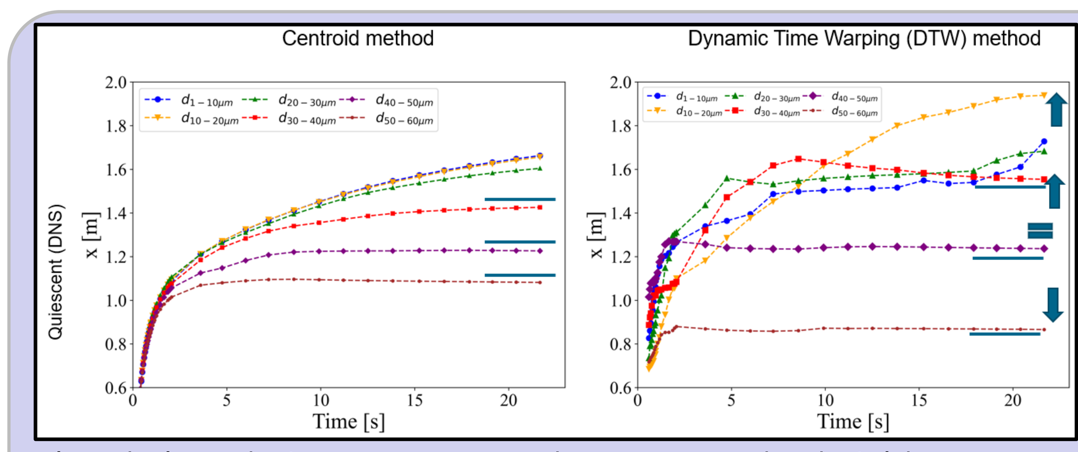
Results



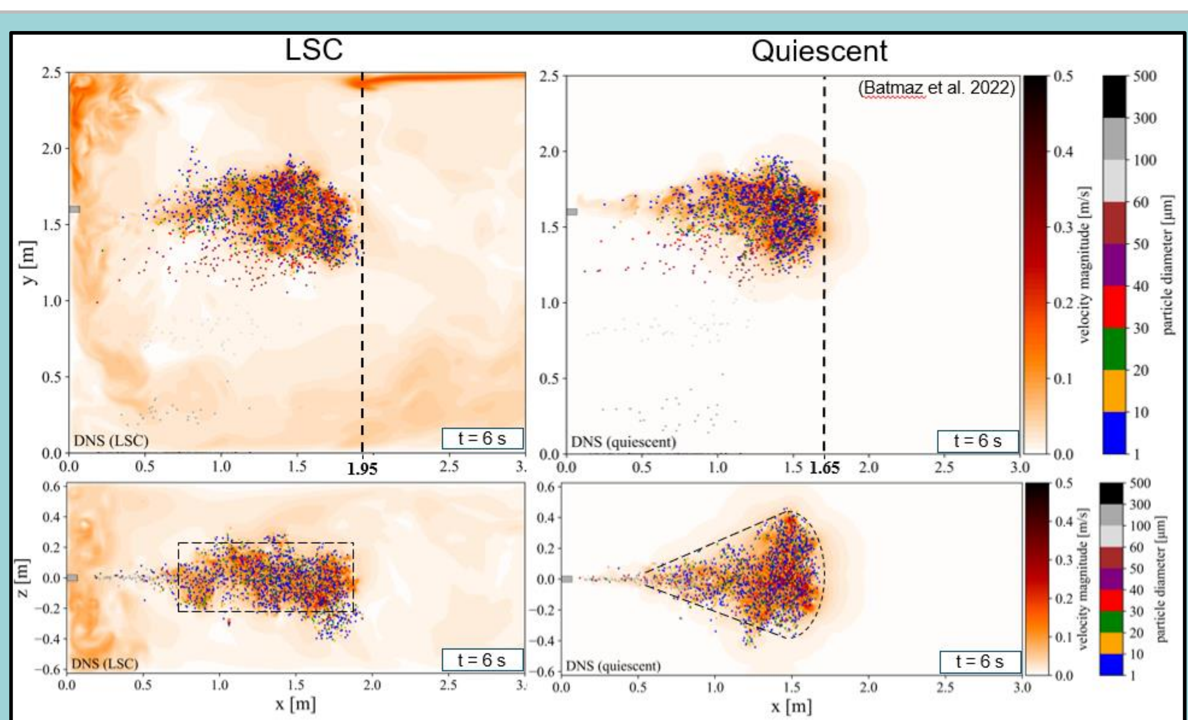
The figure represents the velocity magnitude field, the predicted particle cloud and the velocity magnitude field at the end of the jet phase (t = 1 s). The jet tip and the particle cloud in the LSC case show a larger shift toward the ground compared to the quiescent case. However, the horizontal advancement of the jets are similar. Particles larger than 100 µm have already detached from the jet cloud due to gravitational forces and are approaching the ground with ballistic (semi-ballistic) behaviour.



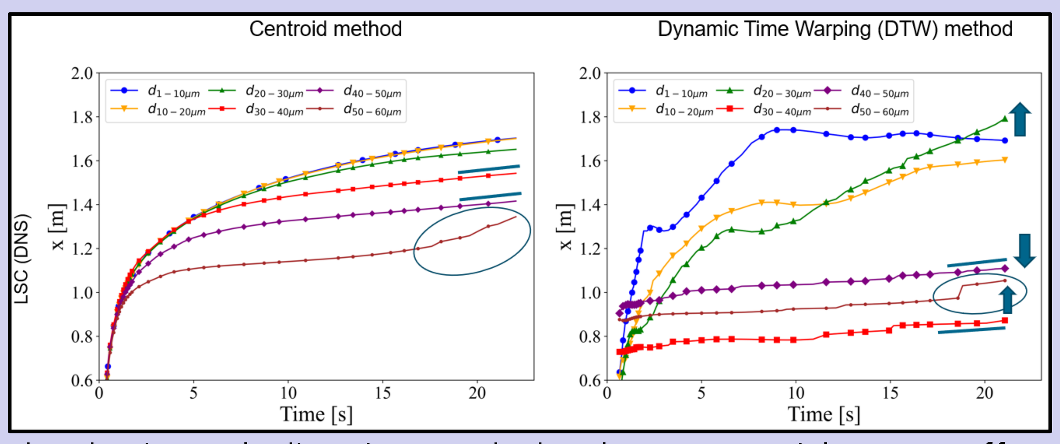
The larger particles advance less in the horizontal direction. This is because the larger particles lose more velocity due to their greater drag. Therefore, as particle size increases, gravitational forces dominate, causing the particles to follow a more pronounced ballistic trajectory. The clear difference between the cases with (solid-line) and without circulation (dashed-line) is that the ballistic behaviour of the particles is slightly delayed for particles belonging to the $d_{30-40\mu m}$, $d_{40-50\mu m}$ and $d_{50-60\mu m}$ size categories, resulting in greater horizontal advancement. Additionally, particles smaller than 20 µm start to rise in both cases after advancing 1.6 m in the horizontal direction due to buoyancy forces.



The graphs present comparisons of horizontal trajectory advancements using centroid and DTW methods in the quiescent case. The horizontal advancements using the centroid method are inversely correlated with the particle size. Particles larger than 30 µm already lost their momentum. The DTW method yields more twisted trajectories and there is no direct correlation between the particle size and the horizontal advancements. Particles within $d_{10-20\mu m}$ advanced the most in 22 s. Larger particles lost their momentum just like using the centroid method but the final reach of the particles within $d_{30-40\mu m}$ and $d_{50-60\mu m}$ changes dramatically.



The figure shows the particle cloud spread from the top and side views, 6 s after the initiation of exhalation, for the quiescent and the LSC cases. The particle cloud in the LSC case spreads 16% farther than the particles in the quiescent case. In addition to the increased horizontal advancement, the maximum lateral spread (in the z-direction) is reduced by 10% and the overall spread is much more uniform instead of a conical shape. The reason for these differences is that the cloud is stretched by the shear forces of the circulating flow acting on the cloud, resulting in a narrower and more elongated shape of the cloud than in the quiescent case.



The graphs present comparisons of horizontal trajectory advancements using centroid and DTW methods in the LSC case. The advancement rates using the centroid method are inversely correlated with the particle size. Larger particles still haven't lost their momentum in the horizontal direction and the largest particles are affected by the strong near-ground circulation and additionally increase their advancement after t = 16 s. The DTW method yields more twisted trajectories and there is no direct correlation between the particle size and the horizontal advancements. Particles within $d_{20-30\mu m}$ travelled the most in 22 s. Larger particles advanced dramatically less compared to the centroid method and keep advancing horizontally. The near-ground circulation enhances the advancement of the particles within $d_{50-60\mu m}$.

Conclusion & Outlook

We studied the impact of a LSC on particle cloud behaviour during the jet phase and puff phase of a single cough. The effect of the LSC on the particle cloud within the jet phase is relatively smaller than the effect of the LSC on the particle cloud within the puff phase, where the LSC enhanced the maximum horizontal advancement of the particles but reduced the maximum lateral spread. DTW method shows twisted particle advancement, more than the centroid method. This difference indicates that the nature of the particle dispersion in a turbulent environment might be more complex than we model and much complex evaluations on the particle spreading might be necessary to model the respiratory aerosol dispersion. In the future, we are planning to extend the simulation time of this LSC case, include particle evaporation and do more observations on the DTW method.

References

[1] E. Batmaz, P. Bahavar, D. Schmeling and C. Wagner. DNS of aerosol particle spreading emitted by coughing and breathing in a simplified room. Accepted for publication in New Results in Numerical and Experimental Fluid Mechanics XIV., NNFM, Springer, 2023.
[2] A. J. Chorin. Numerical solution of the navier-stokes equations. Mathematics of Computation, 22(104), 745–7, 1968.
[3] M. E. Rosti, M. Cavaiola, S. Olivieri, A. Seminara and A. Mazzino. Turbulence role in the fate of virus-containing droplets in violent expiratory events. Physical Review Research, 3(1), 2021.
[4] R. Poletto, T. Craft and A. Revell. A new divergence-free synthetic Eddy Method for the reproduction of inlet flow conditions for Les. Flow, Turbulence and Combustion, 91(3), 519–539, 2013.
[5] J. K. Gupta, C.-H Lin and Q. Chen. Flow Dynamics and characterization of a cough. Indoor Air, 27(1-3), 335–345, 2009.
[6] J. P. Duguid. The size and the duration of air-carriage of respiratory droplets and droplet-nuclei. Epidemiology and Infection, 44(6), 471–479, 1946.

DLR Deutsches Zentrum für Luft- und Raumfahrt

coraero Airborne Transmission of SARS Coronavirus

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