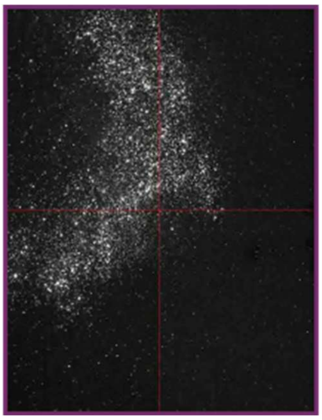
Inertial particles in turbulence

Understanding the behavior of inertial particles in turbulent flows is a central challenge in fluid dynamics, with implications spanning a wide range of natural and industrial processes. For instance, how do raindrops nucleate and grow in clouds? How are plankton dynamics or the transport of microplastics influenced by ocean turbulence? What are the consequences for marine ecosystems and trophic chains? How are pollutants or volcanic ash dispersed in the atmosphere, and what governs their deposition rates? Finally, what are the optimal design parameters for systems such as wastewater treatment plants, combustion engines, or chemical reactors? All of these questions can be addressed by investigating inertial particle dynamics in turbulence. Despite their ubiquity, such flows remain extremely challenging to study due to the large number of intertwined control parameters and the scarcity of predictive theoretical models.

We propose two complementary experimental studies aimed at improving both the physical understanding and empirical modeling of polydisperse particle dynamics in turbulent environments. This research is carried out in collaboration with ENS Lyon, IFPEN Lyon, LMFL Lille, and the University of Buenos Aires. It will benefit from the new **4DFluid platform**, currently being acquired through the SESAME project led by Romain Monchaux, which brings together ENSTA, CEA, ONERA, LadHyX, EM2C, and FAST laboratories.



General framework

Multiphase flows seeded with inertial particles—defined as particles whose intrinsic response times differ from that of the carrier fluid due to their density, size, or shape—are widespread in nature and engineering. These flows play a decisive role in numerous contexts, from cloud microphysics to industrial processes.

Their dynamics are characterized by four key phenomena:

1. **Clustering** – the formation of regions with strongly heterogeneous particle concentrations;
2. **Modified settling velocities** – turbulence may either enhance or reduce the mean settling speed of particles;
3. **Altered collision and coalescence rates** – turbulence affects inter-particle interactions and reactivity;
4. **Two-way coupling effects** – particles can exert feedback on the carrier phase dynamics.

Despite their importance, predictive modeling of these processes remains limited. Most existing approaches rely on strong simplifications, such as treating particles as infinitesimal points or assuming very high concentrations. Even under such constraints, the relevant parameter space for spherical particles is five-dimensional, comprising: the particle-to-fluid density ratio, mass loading, turbulence intensity (Reynolds number), inertia (Stokes number), and relative gravitational forcing (Froude number). The strong interdependence of these parameters explains why the fundamental mechanisms underlying clustering, settling, collisions, and feedback remain only partially understood.

Objectives

Our objective is to investigate the influence of turbulence on inertial particle dynamics using a combination of experiments and numerical simulations in both water and air facilities. **Experiments**, conducted at ENSTA, will simultaneously track particle trajectories and carrier flow fields using advanced high-resolution 3D Lagrangian Particle Tracking (LPT) techniques. Cutting-edge algorithms, such as *Shake-the-Box*, will enable us to capture subtle couplings between particles and turbulence (e.g., relative velocity and acceleration, preferential sampling). Simulations performed by collaborating teams (Buenos Aires, IFPEN) will be used as benchmark.
The initial focus will be placed on measuring particle velocity and acceleration statistics as functions of particle size, density ratio, and turbulence intensity, thus allowing a systematic exploration of the parameter space (particle size, Stokes number, Rouse number, particle-to-fluid density ratio, and Reynolds number). These joint measurements of particles and fluid will make it possible to quantify the relative importance of:

- **Local slip velocity effects** (nonlinear drag contributions),
- **Relative acceleration contributions** (added mass and history forces),
- **Preferential sampling mechanisms** (preferential sweeping or loitering).

This will allow us to distinguish between regimes where turbulence enhances particle settling and those where it inhibits it. At higher seeding densities, we will additionally investigate **collective effects**, such as the coupling between local particle concentrations and modifications of the mean settling velocity.

Supervision

The thesis will be jointly supervised by **Romain Monchaux** (ENSTA Paris) and **Romain Volk** and **Mickaël Bourgoin** (ENS Lyon). Regular meetings, both online and in person, will be organized with the collaborating teams in Lyon, Lille, and Buenos Aires, ensuring close scientific monitoring and sustained collaborative dynamics.

Last publications on the topic:

Dejoan, A. and Monchaux, R. (2025). Settling of not so heavy particles in turbulent flows: insights from 2way coupled direct numerical simulations. In preparation.

Zürner, T., Toupoint, C., De Souza, D., Mezouane, D., & Monchaux, R. (2023). Settling of localized particle plumes in a quiescent water tank. Physical Review Fluids, 8(2), 024301.

Barois, T., Viggiano, B., Basset, T., Cal, R. B., Volk, R., Gibert, M., & Bourgoin, M. (2023). Compensation of seeding bias for particle tracking velocimetry in turbulent flows. *Physical Review Fluids*, *8*(7), 074603.

Application:

Applicants should have a strong background in fluid mechanics and be highly motivated to undertake experimental work. To apply, please send your master's degree marks and a recommendation letter from your former advisor to romain.monchaux@ensta.fr