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Editorial

Focus on dynamics of particles in turbulence

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Abstract
Studies on the dynamics of particles in turbulence have recently experienced advances in experimental techniques, numerical simulations and theoretical understandings. This 'focus on' collection aims to provide a snapshot of this fast-evolving field. We attempt to collect the cutting-edge achievements from many branches in physics and engineering, among which dynamics of particles in turbulence is the common interest. In this way, we hope to not only blend knowledge across the disciplinary boundaries, but also to help the identification of the pressing, far-reaching challenges to be addressed in a topic that spans such a breadth.

Keywords: turbulence, turbulent transport, dispersion, Lagrangian dynamics, inertial particles, collective effects

Most natural and industrial flows are turbulent and contain dispersed inclusions ('particles'). These include, e.g., fuel sprays in combustion engines, pneumatic transport of grains in agriculture, flow of bubbles in chemical reactors, sedimentation in rivers and estuaries, dust/ sand storms, clouds and protoplanetary disks. To study the complicated flow patterns, fluid dynamicists also add tiny tracer particles in the flow for either visualization or quantitative measurements. Understanding the dynamics of the dispersed particles in turbulent flows is therefore of fundamental importance to astrophysicists who are studying the formation of planets, to cloud physicists and meteorologists who are predicting precipitation, to environment policy makers who aim to prevent the occurrence of dust storms, and to engineers who strive to design the best cars.

The problem, on the other hand, is by no means easy. Even a meaningful categorization requires some elaboration. Let us start with dilute inclusion of passive particles. When the particles are small and their densities are comparable with the carrying fluid, they usually follow the local fluid motion. Particles of this type are used as fluid tracers in experimental studies of fluid turbulence. If any of these conditions are not fulfilled, the dynamics of the particles deviate from those of the fluid. Such particles are generically called 'inertial particles'. The situation becomes more complicated if the particles are 'active', e.g., if they can self-propel, such as zooplankton in the ocean, or if the particles exchange mass, momentum or energy with the carrying fluid, such as water droplets in clouds. For both passive and active particles, if the amount of inclusion is high, their presence will modify the underlying turbulent flow itself, which in turn feed back on the dynamics of particles. In facing such a challenging problem (or problems), our available weapons are rather limited. Accurate and detailed measurements have long been difficult. We are still disputing the exact form of equation of motion for non-tracer particles. Most of what we know (or believe to know) today relies on analysis using simplified limiting cases (as the 'point particle' approximation for instance).

However, the situation is changing rapidly. Very important progress has been achieved during the last decade. Advances in measurement techniques have given access to new data with unprecedented temporal and spatial resolutions. Promising numerical approaches have emerged and various theoretical analyses and models have been developed. We are very proud that the contributions to this 'focus on' collection present a balanced coverage of the specific fields involved and the methods used (experimental, numerical and theoretical).

2. Methodological advances

The scientific advances in the comprehension of particle–turbulence interactions represented in this 'focus on' collection are naturally concomitant with new methodological developments, with which more complex situations can be investigated and subtler phenomena can be elucidated.

New methods in numerical simulations. On the numerical aspects, new strategies of large-eddy-simulations (LES) are proposed, with novel sub-grid scale models based on a stochastic differential equation to account for particles inertia [1] and coupling hybrid Eulerian–Lagrangian approaches [2], improving the capacities of LES to handle pair separation and collisions for point-like particles. A long standing limitation of simulations of particles in turbulence was their insufficient capability to address the effects of finite particle sizes, as usual models for particle motion are based on the Maxey–Riley–Gatignol equation that was derived for particles with vanishingly small sizes [3, 4][3]. New methods have emerged in the past few years in order to handle numerically the finite-particle-size effects by fully resolving the flow around particles with size larger than the dissipative scale of the carrier turbulent flow.

[3] An essentially identical equation has also been independently derived by Tsai before [5].

Simulations based on one of such methods, the immersed boundary technique, are presented in [6].

New methods in theory. From the theoretical point of view, this 'focus on' collection exhibits several new approaches capable of addressing important key questions and comparing theories with experiments and numerics. These include new Lagrangian perspectives on the intermittency of both the velocity [7] in fluid turbulence and the magnetic field in magnetohydrodynamic (MHD) turbulence [8], and on the dynamics of rotating turbulence [9]. The non-trivial definition of the 'slip velocity' for finite size particles is discussed in two contributions to this 'focus on' collection [6, 10]. As a natural consequence of being a topic crossing several fields, many theories and mechanisms have been proposed to explain the dynamics of inertial particles in turbulence. It is very welcome to see the illustration of the differences and similarities between several leading theories on the spatial distribution [11] and the relative velocities between inertial particles [12], and the probing of the equivalence between several clustering scenarios [13].

New methods in experiments. On the experimental side, several important advances are also worth mentioning. The development of instrumented particles [14] now gives access to physical quantities (not only kinematic) in the Lagrangian frame, directly measured with sensors embedded in a moving particle. Although limited to relatively large particles (currently in the centimeter range), this new tool opens a whole new range of possibilities, e.g., to probe the fluctuations of temperature and chemical concentration along particle trajectories. After more than a decade of development, image-based particle tracking technique has gained wide application. It was developed for measuring tracer trajectories in turbulence [7], but has been extended to study the dynamics of non-spheric solid particles [10] and gas bubbles [15], as well as to study the collision rate between water droplets in a turbulent air flow [16], an important but very challenging experimental task. At the same time, bias errors in new data analysis methods, such as using Voronoï tessellation of experimental images for preferential concentration diagnosis, are now well understood [17]. Laser Doppler velocimetry (LDV) coupled with particle size analysis, despite being a single-point measurement technique, has the advantage of simultaneously resolving particle velocity and size. When used in a wind tunnel, it could therefore provide measurements of spatial clustering of polydispersed inertial particles by invoking Taylor's frozen-turbulence hypothesis [18], which is not easily achievable with common particle tracking techniques.

In the following sections we briefly summarize the main results that can be found in this collection of papers, which we have organized into the following sub-topics:

- turbulent dynamics of fluid particles (Lagrangian turbulence),
- single particle dynamics of inertial particles and finite-size effects,
- collective dynamics of particles.

3. Turbulent dynamics of fluid particles (Lagrangian turbulence)

When the inertial effects of particles diminish, such as when particle sizes are much smaller than the Kolmogorov scale of the flow and when particle densities match that of the fluid, they follow the fluid motion faithfully. These particles are used extensively in modern turbulence experiments and flow visualizations. Investigating the dynamics of these particles provides us a direct handle on the Lagrangian properties of fluid turbulence.

By studying the evolution of the probability density function (PDF) of the temporal velocity increments along particle trajectories, Wilczek *et al* [7] showed that the non-self-similar, non-Gaussian PDFs (or intermittency) evolve under the control of particle acceleration, a small scale quantity, conditioned on velocity increments, an inertial range quantity. This finding is in full agreement with the commonly accepted view that intermittency comes from the direct interaction between small and large scales, but it also clearly points to the interaction mechanism, at least for the velocity increments.

Further insight on Lagrangian dynamics of turbulence can be obtained from multi-particle statistics. In the past, studies on the dynamics of pairs and tetrads of particles have for instance shed light on dispersion processes [19], and on the role of velocity gradients [20, 21]. In this 'focus on' collection, Naso and Godeferd investigated tetrad dynamics numerically in the context of rotating turbulence [9], which led them to relate turbulence strain and enstrophy production with flow topology. The role of the Zeman scale, at which the local eddy-turnover time and the rotation time scale are equal, was demonstrated to influence multi-scale dynamics of rotating turbulence.

Using direct numerical simulations (DNS), Homann *et al* [8] studied the Lagrangian properties of turbulence dynamics and the magnetic field in a Taylor–Green dynamo. Their result showed a significant impact of the magnetic field, with a strong increase of the correlation time of velocity and magnetic field fluctuations experienced by tracer particles, and an intermittent scaling regime of the Lagrangian magnetic field structure functions.

4. Single particle dynamics of inertial particles and finite-size effects

In spite of the apparent simplicity of the problem, full understanding of the turbulent dynamics of individual particles in turbulence has not emerged yet. The case of small, heavy particles, whose dynamics can be reasonably approximated using the linear Stokes equation (with the Stokes number as the only parameter characterizing particle inertia), has been extensively investigated numerically in recent decades using high resolution DNS in homogeneous isotropic conditions. The knowledge accumulated from this canonical situation offers a solid ground for the development of new numerical strategies in more realistic flow configurations using LES, as mentioned above [1, 2], and for addressing more complex situations where collective effects can arise (see section 5).

Another challenge for a better understanding of particle dynamics concerns the effects of finite particle size. Past experimental results have revealed that these effects cannot be modeled as a simple filtering on the point-particle dynamics [22–24]. Numerical simulations including Faxén corrections have been shown to be accurate only for particles with diameter smaller than a few dissipative scales [25, 26]. These studies therefore called for the development of dedicated numerical tools to investigate finite-particle-size effects [26–29]. In this 'focus on' collection, Kidanemariam *et al* [6] applied the immersed boundary method [27] to study particle transport in non-homogeneous turbulence (channel flow). They showed that the apparent lag of particles dynamics compared to that of the carrier flow was due to the preferential distribution of particles in low-speed streaks. Their work revealed the necessity to redefine the notion of relative velocity between the particle and the fluid, or the 'slip velocity', for the finite-size case, due to local and global inhomogeneities at the scale of the particle. Several strategies, based on local averaging and on velocity fluctuations of the carrier flow in the vicinity of the particle have been proposed in two separate articles of this 'focus on' collection [6, 10].

From the experimental point of view, finite-size effects are of primary importance when measurements with instrumented particles are considered [14], which are in the centimeter scale at present due to technological limitations. Understanding the dynamics of finite-sized particles, for which we do not even have an appropriate equation of motion, is crucial to the interpretation of the information actually gathered by such particles.

5. Collective dynamics of particles

Collective dynamics of inertial particles is probably one of the richest topics of particle–turbulence interaction. The simplest manifestation of such collective effects is the preferential concentration phenomenon, the accumulation of inertial particles in certain regions of the flow due to the interaction between particles and turbulence structures. This inhomogeneous distribution further influences other processes such as particle mixing and dispersion, particle collision and coalescence, settling, flocking, etc.

Many theories have been proposed for quantitative description of the preferential concentration in turbulent flows. Despite all considering only the linear Stokes drag on particles, the available theories differ in appearance, partly due to the different assumptions made and partly due to the complicated derivation involved. In two companion articles, Bragg and Collins [11, 12] analyzed several popular theories on the spatial distribution of small inertial particles in homogeneous and isotropic turbulence and the relative velocities between them. They illustrated clearly the similarities and differences between these theories. By comparing with DNS results, they also showed the ranges of Stokes numbers in which individual theories stayed valid. This 'unification' work is particularly useful in clarifying misconceptions and in identifying the mechanisms that cause the failure of individual theories. In a similar spirit, Gustavsson *et al* [13] investigated the concentration fluctuations of particles in a random flow from kinematic simulations at various Kubo numbers, which characterizes the correlation time of the velocity field. They compared three mechanisms of particle collective dynamics: random uncorrelated motion, caustics and spatial clustering as a consequence of the deformation tensor, and showed in particular the equivalence of the last two.

Enhancement of the droplet–droplet collision frequency by the interaction between water droplets and turbulence is believed to be a key mechanism in the acceleration of rain initiation in warm clouds [30, 31]. Collision rate is directly related to the radial distribution function (RDF) and the radial relative velocity (RRV) between pairs of particles. Using high resolution DNS up to $R_\lambda \sim 500$, Rosa *et al* [32] investigated numerically the RDF and the RRV, addressing particularly their dependence on Reynolds number and gravity. The results suggested a saturation of the behavior of pair statistics at high Reynolds numbers, and a complicated effect of gravity on the collision rates of large particles (roughly corresponding to cloud droplets above 20 μm in diameter), while smaller ones are insensitive to gravity. Bordas *et al* [16] measured experimentally the collision rates between water droplets in wind tunnel turbulence, and compared experimental results with collision rates obtained theoretically that include: (i) only gravitational settling; (ii) gravitational settling and turbulence; and (iii) settling and turbulence and change of collision efficiency due to hydrodynamic interactions between particles when approaching. Although quantitative agreement was only partially supported, theories including both turbulence and collision efficiency gave closer predictions when confronted with experimental measurements. The role of turbulence on collision enhancement was also clearly established in the LES simulation by Riechelmann *et al* [2].

In real particle-laden flows, such as in clouds, the particle sizes are not uniform but distributed over a range. This polydispersity further complicates the interaction between particles, and between particles and turbulence. In this 'focus on' collection, the role of polydispersity was addressed in two companion articles by Saw *et al* [18, 33], which combined theoretical, numerical and experimental studies of the radial distribution function for both monodisperse and polydisperse situations. Their study pointed out the leading role of dissipative motion on the clustering process (at least for particles with Stokes number below 0.3) and the necessity to correctly disentangle large scale mixing effects from the preferential concentration in experiments. The numerical investigation of a population of particles with two different Stokes numbers exhibited a saturation effect, which was limited by the least clustered population. Based on theories and simulations on polydispersed systems, they proposed a new analytical form for the radial distribution function for any distribution of particle sizes.

Particles could also interact with the carrier fluid through phase change, for example, the condensation/evaporation of water droplets in clouds, during which the particles exchange both mass and thermal energy with the fluid. Kumar *et al* [34] investigated numerically the role of evaporation at the entrainment edge of clouds. Their study illustrated the effect of the Damköhler number, Da, which compares the typical flow time scale to the typical evaporation time scale, on the evolution of droplets size distribution: minimal broadening of size distribution was observed when $Da \ll 1$ while a strong negative skewness developed when $Da \gg 1$.

The collective dynamics become even more complex when particles are active. Khurana and Ouellette [35] studied the effect of environmental fluctuations, which could be random or with turbulence-like structures, on the stability and the dynamics of model particle flocks. Their surprising result was that even a low level of turbulence-like fluctuations was sufficient to destabilize flocks. This work revealed an unexpected impact of flow on collective animal motion, whose accurate modeling needs to take realistic background fluctuations into account.

6. Conclusion and perspectives

This collection of articles reflects significant progress achieved during the last decade in the understanding of particle–turbulence interactions. It provides a snapshot of this fast-evolving field, with the latest methodological developments (theoretical, numerical and experimental). Advances in Lagrangian measurement techniques (optical particle tracking, shadowgraphy, instrumented particles) now give access to new data with unprecedented resolution. New, promising numerical approaches have emerged. For instance, the dynamics of finite size particles can be fully resolved and coupled with the DNS of the carrier flow without any *a priori* modeling. Various theoretical approaches have also been proven successful, including stochastic and PDF models, and analysis capable of giving new insights on relevant physical mechanisms, such as the polydispersity of particle sizes.

Let us finish by noting that, compared to the breadth of the particle–turbulence interaction problem, this 'focus on' collection is far from being exhaustive. Although it highlights some of the most important latest developments, it only covers a small part of the full landscape of related ongoing research activities. There are many aspects for which new developments are still crucial. To name a few, almost all theoretical investigations and most of the numerical simulations of the dynamics of inertial particles consider only the Stokes drag. Some may include finite Reynolds number corrections and some may include the added mass. The effects of other terms, such as the history forces, however, have been largely ignored even without solid justification. No comprehensive investigation of the consequences of all these simplifications exists at the moment, which might help explain why the few available numerical studies including these extra forces do not seem to give the same conclusion (see, e.g., [36–38]). This collection is awaiting clarification, most likely by extensive numerical simulations. On the front of measurement techniques, an important step forward concerns the ability to access simultaneous conditional diagnosis. For instance it would be extremely useful if the velocities and sizes of all particles in the observation region could be simultaneously resolved, which would allow accurate study of the collision rates and will be invaluable for field measurements where the particle sizes are not under control. Furthermore, simultaneously accessing the velocities of the particles and the local velocity of the carrier flow, as demonstrated for large neutrally buoyant particles in turbulent flows [39], will help in gaining a better insight into the coupling mechanisms between particles and the flow. These experimental challenges require the combination of several techniques (Lagrangian particle tracking, particle sizing, local tomographic or holographic methods around particles, etc). Given the rapid development we are experiencing, we are optimistic that all these mentioned above will be adequately addressed in the near future.

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