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# Clustering and Settling of Inertial Particles in Turbulence

Sholpan Sumbekova, Alberto Aliseda, Alain Cartellier  
and Mickael Bourgoïn

**Abstract** Particle laden flows are of a great interest in many industrial and natural systems. When the carrier flow is turbulent, a striking feature named preferential concentration takes place: particles denser than the carrier fluid tend to inhomogeneously distribute in space, forming clusters and depleted regions. The present study aims at giving new insight into the possible connection between preferential concentration and particles settling in homogeneous isotropic turbulence. Preferential concentration is quantified using Voronoï diagrams, while 2D Lagrangian Particle Tracking is used to access particles dynamics and in particular statistics of settling velocity. Independent and joint statistics of local concentration and settling velocity are discussed. More particularly, the possible dependence of particle settling rates on clustering properties are investigated.

## 1 Introduction

A striking feature of turbulent flows laden with inertial particles is the so-called preferential concentration (or clustering) that leads to strong inhomogeneities in the particles concentration field at any scale. This has now been widely observed in

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S. Sumbekova (✉) · A. Cartellier  
Université Grenoble Alpes, LEGI, F-38000 Grenoble, France  
e-mail: sholpan.sumbekova@legi.grenoble-inp.fr; sholpan.sumbekova@ujf-grenoble.fr

S. Sumbekova · A. Cartellier  
CNRS, LEGI, F-38000 Grenoble, France  
e-mail: alain.cartellier@legi.grenoble-inp.fr

A. Aliseda  
Department of Mechanical Engineering, University of Washington,  
Stevens Way, Box 352600, Seattle, WA 98195, USA  
e-mail: alberto.aliseda@u.washington.edu

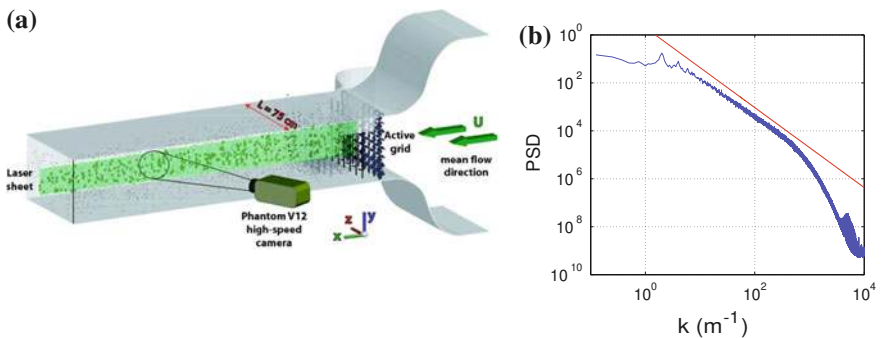
M. Bourgoïn  
Laboratoire de Physique, Univ Lyon, ENS de Lyon, Univ Claude Bernard, CNRS,  
F-69342 Lyon, France  
e-mail: mickael.bourgoïn@ens-lyon.fr

many experimental and numerical realizations including homogeneous and isotropic turbulence [3, 10, 11]. Several properties of preferential concentration seems now to be robustly established with consensual results in the litterature [8, 9]. We can mention among others: (i) the fractal geometry of clusters, (ii) the fact that the typical clusters scale is of the order of ten times the Kolmogorov scales of the carrier turbulence and (iii) the fact the maximal clustering effects are observed for particles whose Stokes number (defined as the ratio of the particle relaxation time to the Kolmogorov viscous time of the carrier turbulence) is close to unity. However, a clear theoretical description of preferential concentration remains a challenge, in particular regarding the specific mechanism(s) leading to clustering [5, 6] and the further impact clustering may have on the collective dynamics (and particularly on the settling rate) of particles [1]. An important question addressed in the present study concerns the possible enhancement of settling velocity within clusters, as reported by Aliseda et al. [1], and more generally the connection between local particle concentration and settling properties.

Recently, our group has introduced Voronoï tessellations analysis, obtained from snapshots of the particles in a given area in a flow field, to quantify clustering [7, 8]. Here we propose to take benefit of the capacity of such analysis to be coupled to Lagrangian tracking of particles, in order to investigate the interplay between clustering and settling. Our experimental study gives access to unprecedented statistics of settling velocity conditioned to particles local concentration field, whose first results are presented in this article.

## 2 Experimental Setup

Experiments are conducted in a large wind tunnel with a square cross-section of  $0.75\text{ m} \times 0.75\text{ m}$  (see Fig. 1a). Turbulence is generated with an active grid [9], capable to produce moderate to high turbulence with still relatively good homogeneity



**Fig. 1** **a** Sketch of the experimental setup. **b** Typical velocity spectrum of turbulence produced by the active grid (*red solid line* represents a  $k^{-5/3}$  trend)

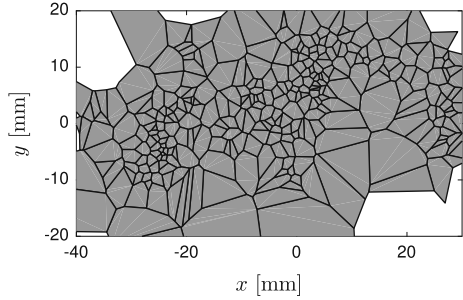
and isotropy levels. The mean stream velocity  $U$  of the wind was varied from 2.5 to 10 m/s. The active generates velocity fluctuations with a turbulence intensity (defined as the ratio between the standard deviation of velocity  $\sigma_U$  to the mean stream velocity  $U$ ) of the order of 20 %. The corresponding Reynolds number based on Taylor microscale,  $Re_\lambda = \sigma_U \lambda / \nu$  ranges between 200 and 500 ( $\lambda = \sqrt{\frac{15\nu}{\epsilon}} \sigma_U$  is the Taylor microscale, with  $\nu = 1.5e - 5 \text{ m}^2\text{s}^{-1}$  the kinematic viscosity of air at working temperature and  $\epsilon$  the turbulent energy dissipation rate per unit mass). Figure 1b represents a typical velocity spectrum of the turbulence produced by the active grid. Inertial particles are water droplets generated by 18 injectors located in a transverse plane 15 cm downstream the grid. The average diameter of the particles is constant for all velocities, with a typical mean sauter diameter  $D_p \simeq 60 \mu\text{m}$  (although size distribution has a significant polydispersity of the order of 50 %). We define the typical Stokes number of the particles as  $St = \frac{1}{36} \left( \frac{D_p}{\eta} \right)^2 (1 + 2\rho_p/\rho_f)$ , with  $\eta$  the Kolmogorov dissipative scale of the carrier turbulence and  $\rho_p/\rho_f$  the particle to fluid density ratio (which in our case, water particles in air, is of the order 815). In our experiments, the size of the particles is kept constant, and variations of Stokes numbers are explored by varying the dissipation scale  $\eta$  of the flow, which decreases as the wind velocity increases. Stokes and Reynolds number are therefore linked parameters, which do not vary independently. Further experiments will be carried in near future to disentangle more precisely Stokes and Reynolds number effects. Note also that in our experiments the flow rate of water through the atomizing injectors producing the droplets is kept constant. This means that the particle volume fraction given by  $\frac{Q_L}{Q_L+Q_G}$ , where  $Q_L$  is an injected flow rate and  $Q_G$  is a main air flow rate within the flow decreases linearly as the wind speed increases. Finally, a longitudinal laser sheet (with millimetric width) is used to illuminate the particles (as shown in Fig. 1). Images were recorded with one high speed camera Phantom V12 from Vision Research Inc., with a field of view of the order of the integral scale of the carrier flow of 12 cm.

## 3 Results

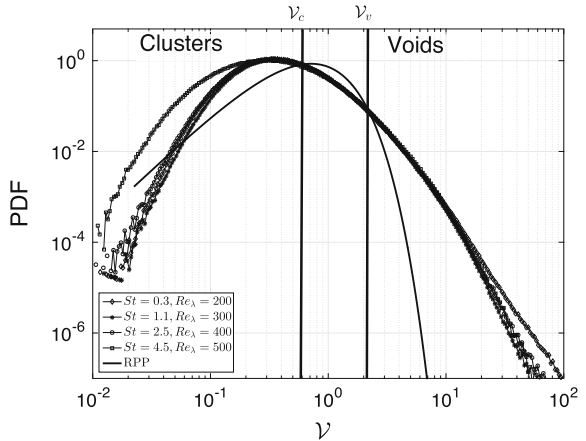
### 3.1 Voronoï Tessellations

Voronoï analysis is used for quantifying the phenomenon of preferential concentration [7, 8]. Voronoï diagrams give a tessellation of 2D space (though the analysis can be extended to any spatial dimension) where each cell of the tessellation is assigned to a particle, with all points of one cell closer to its associated particle than to any other particle. Figure 2 shows the tessellation of one instantaneous recorded image. Each visible cell (we shall refer to cells as *Voronoï cells*) contains one unique particle. Consequently, the inverse area of each Voronoï cell represents the local concentration

**Fig. 2** Example of Voronoi tessellation. Each Voronoi cell contains a unique particle



**Fig. 3** PDF of normalised Voronoi areas  $\mathcal{V}$ . The *solid line* represents the Voronoi area PDF expected for a Random Poisson Process, which is well approximated by a Gamma function [2]



of particles. The higher the local concentration of the particle, the smaller its corresponding Voronoi area  $\mathcal{A}$ . Figure 3 shows the probability density function (PDF) of normalized Voronoi cell areas  $\mathcal{V} = \mathcal{A} / \bar{\mathcal{A}}$  (where  $\bar{\cdot}$  represents the ensemble average over the full set of images for each experiment) for the several experiments we carried at different wind velocities (hence different Stokes and Reynolds numbers). The deviation of the experimental PDF compared to the PDF expected for a pure random Poisson process (RPP), represented by the solid line in the figure, is representative of the existence of preferential concentration, as small areas (dense regions) and large areas (depleted regions) are over-represented in the experiments with respect to the RPP case. A detailed description of trends of clustering with Stokes and Reynolds number in our experiment goes beyond the scope of the present article, but can be found in [9]. We can just emphasize here that, in the range of parameters explored here, the level of clustering is significant (this can be quantified by the standard deviation of the PDFs shown in Fig. 3, which is of the order  $\sigma_{\mathcal{V}} \simeq 1.2$ , while the corresponding value for a RPP is  $\sigma_{\mathcal{V}}^{RPP} \simeq 0.53$ ) with a weak dependency on the explored parameters, although small areas (over-concentrated regions) are slightly over-represented for the largest Stokes numbers explored and large areas (under-concentrated regions) are for the lowest Stokes numbers explored (note however that this effect appears amplified

by the log-log representation of the figure, but contributes marginally to the change of  $\sigma_{\mathcal{V}}$ , which remains in the range  $\sigma_{\mathcal{V}} \in [1.1, 1.25]$  for the full set of experiments).

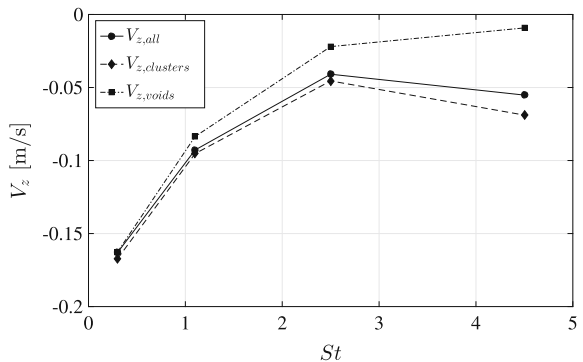
We use now the comparison between the measured PDFs and the RPP PDF to determine clusters and voids, following the definition proposed by Monchaux et al. [7]: *clusters* and *voids* are composed, respectively, by Voronoï cells feeding the small and large area tails of the PDF, corresponding to over-represented events with respect to the RPP case. Intersections of the measured PDFs and the RPP PDF near the maximum therefore define two thresholds  $\mathcal{V}_c$  and  $\mathcal{V}_v$  (with  $\mathcal{V}_c < \mathcal{V}_v$ ) such that cells with normalized area below  $\mathcal{V}_c$  belong to clusters and cells with normalized area above  $\mathcal{V}_v$  belong to voids. In our experiments, we found that these thresholds do not depend significantly on the experimental parameters (Stokes number or Reynolds number) and we have  $\mathcal{V}_c \simeq 0.6$  and  $\mathcal{V}_v \simeq 2.1$  (see Fig. 3).

### 3.2 Joint Analysis of Concentration and Settling Velocity

Particle Tracking Velocimetry was used to reconstruct particle trajectories and measure the instantaneous velocity of each individual particle. In the present case, the use of one single camera and a laser sheet illumination allows to access 2 components of particles velocity in the illumination plane. The key point of the present study is that besides this information on particles velocity, the above mentioned Voronoï analysis allows to attribute to each individual particle an instantaneous Voronoï area (representing the instantaneous local particle concentration in the vicinity of each particle). We can therefore consider accessing joint statistics of particles local concentration and velocity.

Figure 4 shows the dependence of the average settling velocity  $V_z$  on Stokes number (or equivalently on Reynolds number) for three types of particles in each experiment: (i)  $V_{z,all}$  refers to the average settling velocity of the full set of particles, regardless of the value of their associated Voronoï area (ii)  $V_{z,cluster}$  refers to the average settling velocity of particles belonging to clusters only (*i.e.* we condition

**Fig. 4** Mean settling velocity calculated (i) for the full set of particles for each experiment ( $V_{z,all}$ ), (ii) for particles belonging to clusters only ( $V_{z,clusters}$ ) and (iii) for particles belonging to voids only ( $V_{z,voids}$ )



the average of settling velocity by keeping only particles with Voronoï area  $\mathcal{V} < \mathcal{V}_c$ ) and (iii)  $V_{z,voids}$  refers to the settling velocity of particles belonging to voids only (*i.e.* we condition the average of settling velocity by keeping only particles with Voronoï area  $\mathcal{V} < \mathcal{V}_c$ ). Several points are worth being highlighted and discussed from this plot:

1. All curves follow a similar trend, with globally a reduction of settling velocity with increasing Stokes number (or equivalently in our case with increasing Reynolds number). For the largest Stokes numbers explored we may observe a saturation, or even a decrease (except for particles in voids). Since the particle diameter is kept constant, this effect is purely due to the interaction between the particles and the carrier turbulence. Further studies are required to draw robust conclusions on these trends. In particular, when turbulence and inertia contribute to enhance or reduce settling is a subtle matter, as shown by a recent study focusing on the case of individual particles (in very dilute conditions) in turbulence [4]. A systematic study, where seeding concentration, Stokes number and Reynolds number are varied independently is a requisite to identify robust generic trends. This goes beyond the scope of the present article, but will be addressed in coming studies.
2. The most striking feature on the curves in Fig. 4 is the systematic difference between the settling rate of particles in clusters compared to particles in voids. Clustered particles settle systematically faster than particles in voids. Besides, this difference increases with increasing Stokes number (or increasing Reynolds number). This observation is consistent with measurements reported by Aliseda et al. [1]. A natural question now concerns the possible origin of this effect. Two main mechanisms can be considered: (i) a signature of preferential sampling of the turbulent flow by the particles, in the spirit of the preferential sweeping mechanism, where clusterized particles would for instance explore preferentially high strain downward regions [6] or (ii) a role of collective effects, where the collective settling of clusters would enhance the individual settling of particles [1]. In our experiment, we observe that the level of clustering (which can be quantified for instance by the standard deviation of the normalized Voronoï areas) does not vary by more than 10% over the range of Stokes number (or Reynolds number) explored here. We therefore do not expect a significant difference in the way particles preferentially sample the turbulence and believe that the observed trends are mostly attributable to collective effects. A possible dominant role of collective effects is further supported by the fact that the particle volume fraction is reduced by almost a factor 4 between the experiments at lowest wind-speed (*i.e.* lowest Stokes number) and those at higher wind-speed (*i.e.* higher Stokes number)), that impacts the overall concentration, but also the concentration within clusters and voids, and hence is expected to modify the collective settling behavior [1].
3. Even if this may seem obvious, it is still worth pointing that the fact that the global mean settling velocity follows more closely the settling velocity of clustered particles (rather than particles in voids) is expected as, by essence, particles in voids are less numerous and therefore contribute less to the global mean.

## 4 Conclusion

By combining Voronoï analysis of the concentration field of inertial particles in turbulence and Lagrangian particle tracking, we have shown that in presence of preferential concentration, particles within clusters settle systematically faster than particles in voids, what we tend to attribute to the additional influence of collective settling of clusters. Further studies are now required to support this interpretation and to understand other observed trends (as the diminution of settling rate with increasing Stokes number). In particular, carrying experiments where Stokes number, Reynolds number and seeding concentration are varied independently is of primary importance. Such experiments are in progress at the moment.

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