Effect of electric charge on dispersion and spatial distribution in particle-laden turbulent flows

Athanasios Boutsikakis[1], *Pascal* Fede[1,*], and *Olivier* Simonin[1]

[1]Institut de Mécanique des Fluides de Toulouse (IMFT), Université de Toulouse, Toulouse-INP ENSEEIHT, CNRS, Toulouse, France

Abstract. The effect of electric charges carried by particles in homogeneous isotropic turbulent flow is analysed. Direct Numerical Simulations have been coupled with the Lagrangian tracking of particles and a specific algorithm accounting for the inter-particle electrostatic force of particle having the same electric charge. In the first configuration where the gravity is neglected, the effect of the electric field on the spatial distribution of particles is shown. According to the level of the charges, the radial distribution function of pair particles exhibits an exclusion zone in which the probability to have a second particle is null. In that case, a competition exists between the repulsive electrostatic forces and the particle-turbulence interactions which may lead the particles to preferentially concentrate. When the gravity is accounted for, the fluctuating motion of the particles in the direction of the gravity and in the normal direction normal are different. Similarly to the inter-particle collisions, the electrostatic forces lead to the isotropization of the particle motion which can be modelled in the framework of the kinetic theory.

1 Introduction

Turbulent particle-laden flows are very common in many applications such as the powder transport (pneumatic conveying), pharmaceutical and medical applications (drug inhalation, virus dispersion by sneezing), space exploration (landing on Mars), renewable energy (dust deposition on photovoltaic panel) or geophysical flows (volcano ashes dispersion, sediment transport). In all of these applications, many complex phenomena take place such as the particle dispersion, collision/bouncing, attrition/abrasion, electrostatic forces, or chemical reaction.

Inter-particle collisions, or particle-wall rebounds, may cause the particles to be electrically charged. The charges, carried by the particles, create an electric field which in turn affects the particles motion. When particles are transported by a turbulent flow, according to their inertia (characterized by the Stokes number) the particles may concentrate in low-vorticity region of the turbulent flow [5]. In 2010, Lu et al. [7] conducted experiments and they showed that the radial distribution function of particle pair, giving the probability of having a second particle at a given distance, is decreased when the particles are identically charged. This important result is restricted to particles having low inertia namely with a Stokes number, based on the Kolmogorov's timescale, of 0.3 and 0.6. In the present work, we investigate the case of particles having a larger Stokes numbers from 1.0 up to 100 which correspond for Stokes numbers based on integral time scale from $\tau^F_{fp}/\tau^t_f = 0.17$ to 20 where τ^F_{fp} is the particle response time to the fluid flow (i.e. the drag force force) and τ^t_f the integral timescale of the turbulence.

In the literature several studies have been dedicated to the settling of charged particles. However, the focus was only made on the particle clustering whereas as shown by [2] the first effect of electric charges is to modify the particle fluctuating motion. Then the second part of the study is dedicated to analyse the crossing trajectory effect for charged particles. As shown by Yudine (1959) [8] and later by Csanady (1963) [4] when it exists a mean slip velocity between the gas and the particles, as for example due to the gravity, the dispersion of the particles is not the same in the direction of mean slip velocity and in its normal direction. Here we analyse how the electrostatic forces modify the crossing trajectory and if the electrostatic forces lead to the isotropisation of the particle fluctuating motion as the inter-particle collisions do.

2 Numerical simulation overview

We consider an ensemble of N_p solid spherical particles electrically like-charged with a charge Q_p and transported by a Homogeneous Isotropic Turbulent flow. The density of the particles being large compared to the fluid one the particle motion governing equations read

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{u}_p \qquad \text{and} \qquad m_p \frac{d\mathbf{u}_p}{dt} = m_p\mathbf{g} + \mathbf{F}_D + \mathbf{F}_e \quad (1)$$

where $\mathbf{x}_p$ is the particle centre-of-mass position, $\mathbf{u}_p$ the particle translational velocity, m_p the particle mass, and $\mathbf{g}$ the gravitational acceleration. In (1), $\mathbf{F}_D$ is the drag force exerted by the fluid on the particles and is written as

$$\mathbf{F}_D = -\frac{\mathbf{u}_p - \mathbf{u}_{f@p}}{\tau_p} \quad (2)$$

*e-mail: pascal.fede@imft.fr

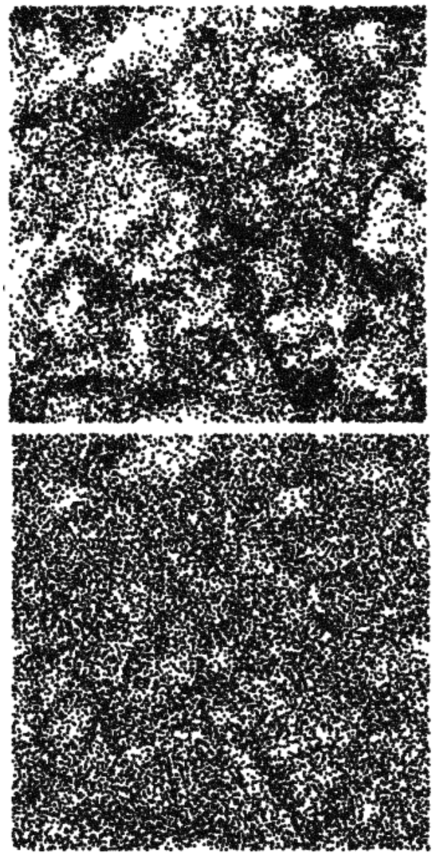

Figure 1. Instantaneous distribution of particles transported by a turbulent fluid flow without electric charge (top) and with electric charge (bottom).

with $\mathbf{u}_{f@p}$ being the fluid velocity at the particle position. In (2), the timescale τ_p is given in terms of the material properties of the particles (see for example [1] for more details). Such a timescale allows to define the particle relaxation timescale τ_{fp}^F defined as

$$\frac{1}{\tau_{fp}^F} = \left\langle \frac{1}{\tau_p} \right\rangle \quad (3)$$

where $\langle \, . \, \rangle$ is the ensemble average operator.

The last term in (1) is the electrostatic force acting on the particle. Here, only Coulombian interactions are considered. The force acting on a given particle results from the interactions with all other particles. Hence

$$\mathbf{F}_e = \sum_{q=1, q\neq p}^{N_p} \mathbf{F}_{e,q\to p} \quad (4)$$

where

$$\mathbf{F}_{e,q\to p} = \frac{Q_p Q_q}{4\pi\epsilon_0 ||\mathbf{r}_{pq}||^3} \mathbf{r}_{pq} \quad (5)$$

with ϵ_0 being the permittivity of vacuum and $\mathbf{r}_{pq} = \mathbf{x}_p - \mathbf{x}_q$ the distance vector between the p and q particles. Such a model has been successfully used [2] however it does not take into account the effect of dipole as proposed by Giordano et al. [6]. From a numerical point of view the computation of the electrostatic forces is very time consuming

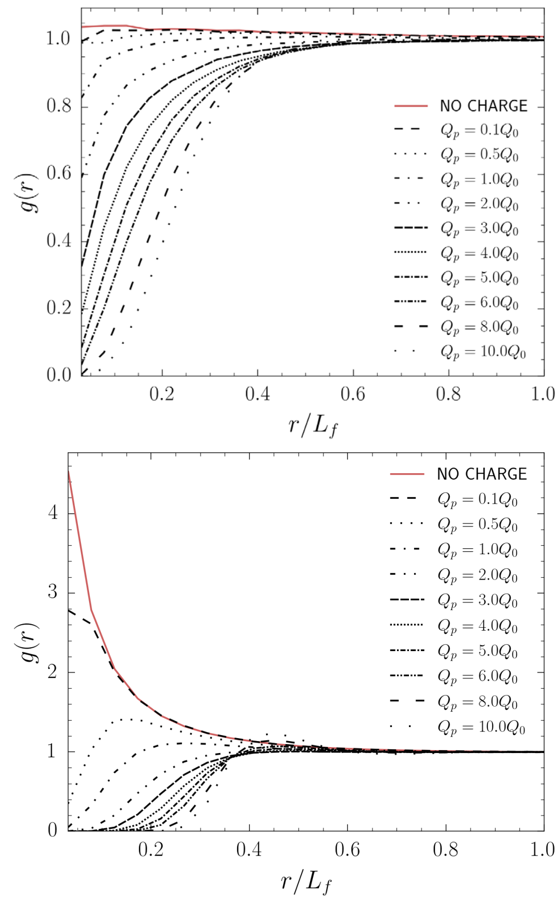

Figure 2. Radial distribution function for $\tau_{fp}^F/\tau_f^t = 7.57$ (top) and $\tau_{fp}^F/\tau_f^t = 0.17$ (bottom) with respect to the electric charge. The particle-pair distance r is normalized by turbulent integral length scale L_f representing the size of the biggest turbulent eddies.

because it requires to compute all distances between particles. More, in the present case, three-dimensional periodical boundary conditions are applied and, as shown by [3], it requires a very specific care for ensuring an accurate computing of electrostatic force but also its isotropic nature.

3 Effect of electric charges on particle clustering

When particles are transported by a turbulent fluid flow, according to their Stokes number (i.e. τ_{fp}^F/τ_f^t) they may accumulate in low-vorticity regions [5]. This phenomena, commonly called preferential concentration, is shown by 1. One can observe that when the electrostatic forces are accounted for the particle distribution becomes much more uniform.

In the literature several markers have been proposed to analyse the particle clustering. However, in the kinetic theory of particle-laden turbulent flows the particle spatial distribution appears through the Radial Distribution Function $g(r)$, called hereafter RDF, giving the probability of having a second particle at a given distance r. Hence, by

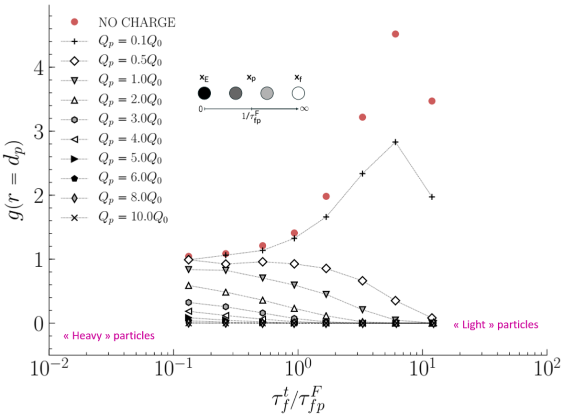

Figure 3. Radial distribution function at a particle diameter distance with respect to the electric charges and the inverse of the Stokes number τ_f^t/τ_{fp}^F.

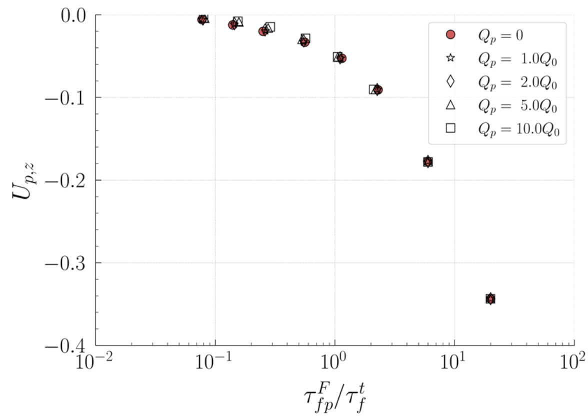

Figure 4. Mean particle velocity with respect to the Stokes number τ_{fp}^F/τ_f^t and the particle charges. The red filled symbols are the case without electrostatic forces.

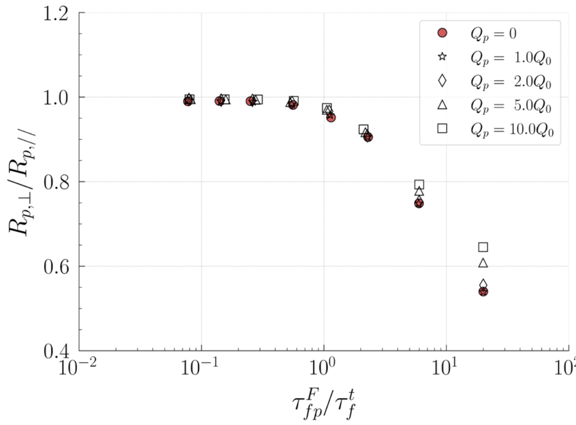

Figure 5. Ratio between the normal to the parallel particle velocity variance (top) and fluid-particle velocity covariance (bottom) with respect to the Stokes number τ_{fp}^F/τ_f^t and the particle charge. The red filled symbols are the case without electrostatic force.

definition, if the particles are uniformly distributed over the space, the RDF equals to one. When particle clustering is present the RDF is larger than one at short distances and goes to one for larger distances. These trends are shown by Fig. 2 where the case without electric charge is shown by the solid red lines. For the large Stokes number, corresponding to heavy particles, namely $\tau_{fp}^F/\tau_f^t = 7.57$ the RDF is almost one meaning no clustering. In contrast, for the Stokes number, $\tau_{fp}^F/\tau_f^t = 0.17$ the solid red lines deviates from one for larger value indicating clustering. When the particles are charged, the RDF is found decreased for a given distance. More for the light particles, an exclusion zone appears where $g(r)$ goes to zero meaning that statistically no particles can be found in this zone. The physical meaning of this is that the repulsive forces, due to the charges, do not allow the particles to be found under a given distance of separation.

The effect of the Stokes number on this peculiar behaviour is also shown by Fig. 3 where the RDF at a distance of one particle diameter is shown with respect to the Stokes number. Figure 3 allows to extend the observations of Lu et al. (2010) [7] for a wide range of Stokes number.

4 Dispersion of like-charged particle settling in homogeneous isotropic turbulent flow

When the gravity is accounted for, the mean particle velocity is no longer zero. Figure 4 shows the mean particle velocity with respect to the Stokes number. As expected, increasing the Stokes number, i.e. increasing the particle inertia, leads to increasing the magnitude of the mean velocity. More interesting, one can observe that the electrostatic forces have no influence on the mean particle velcoity.

When a mean gas-particle slip velocity exists it leads to the crossing trajectory effect [8]. As a consequence of the mean gas-particle slip velocity, the particle velocity fluctuating motion becomes anisotropic and the particle velocity variance in the direction normal to the mean slip, $R_{p,\perp} = \langle u'_{p,\perp} u'_{p,\perp} \rangle$, is smaller than the one in the parallel direction, $R_{p,\parallel} = \langle u'_{p,\parallel} u'_{p,\parallel} \rangle$, as shown by Fig. 5.

Figure 5 shows that when the particles are like-charged the anisotropy of the particle motion decreases especially for the particles with large Stokes number. By analogy with the inter-particle collisions, this effect could be predicted in the framework of the kinetic theory where the isotropization is modelled by a return to equilibrium term proportional to the collision frequency. Here, the collision frequency could be replaced by Coulombian collision frequency has been proposed by Boutsikakis et al. [2] for modelling the effect of electric charges on the particle self-dispersion.

5 Conclusions

The study investigated the effects of electrostatic forces of like-charged particles in homogeneous isotropic turbulent flow. In the first case, the effect of the electrostatic forces on the particle spatial distribution has been investigated for large Stokes number. One showed that the repulsive forces, due to like-charged particles, leads to exclusion zone around the particles. The size of this zone decreases for decreasing the Stokes numbers. For settling particles, the electrostatic forces have no effect on the mean particle velocity however it has been observed an isotropization of the particle fluctuating velocity.

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