A numerical study of finite size particles in homogeneous turbulent flow

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Abstract

The present study addresses finite size and finite Reynolds number effects in spatially homogeneous turbulent flow seeded with solid particles. The ratio between particle diameter and Kolmogorov length scale is chosen in the interval 5-25; the Reynolds number based upon the particle diameter and the terminal velocity in ambient flow is of order $O(100)$. Under these conditions, the point-particle approach loses its validity, and we resort to fully-resolved simulations, realized with the aid of an immersed boundary method. The volume fraction of the solid phase is set to $5 \times 10^{-3}$, whereby dominant effects of inter-particle collisions are avoided. Two flow configurations are investigated: pure sedimentation in ambient fluid and sedimentation with decaying turbulent background flow, both without mean velocity gradients and with periodicity in all spatial directions. It is found that turbulence has a strong effect upon the settling velocity, initially causing a significantly slower average vertical particle velocity, and at later times (when the turbulence intensity has decayed to a weaker level) a slightly more rapid settling. At the same time turbulence is found to affect the inter-particle distances, bringing particles closer together than pure sedimentation. Further effects of settling particles upon the turbulent kinetic energy, the dissipation rate and anisotropy are discussed, as well as probability density functions of particle velocities and forces.

Introduction

The interaction between finite-size heavy particles and a surrounding flow field is a fundamental hydrodynamic problem with applications to various real-world configurations, such as raindrop formation in clouds, fluidized bed reactors and combustion devices. In past studies the details of the near-field around the particles have often been neglected, thereby excluding a description of wake effects (cf. Balachandar and Eaton 2010, for a recent review). Here we consider sedimentation problems involving particles with diameters between 10 and 25 Kolmogorov length scales and average particle Reynolds numbers (based upon diameter and settling velocity) of $O(100)$. For this purpose we have carried out direct numerical simulations with interface resolution. Today these computations are still costly and limited to a narrow parameter range. However, numerical experiments are able to complement laboratory measurements, in particular by providing data at high spatial and temporal resolution.

The problem of particles settling in a turbulent background flow is characterized by a large set of non-dimensional parameters. Let us first consider the case of sedimentation of a set of mono-disperse spheres in an ambient fluid. Given the fluid density $\rho_f$, the kinematic fluid viscosity $\nu_f$, the vector of gravitational acceleration $g$ on the one hand, and the particle diameter $D$, particle density $\rho_p$ and solid volume fraction $\Phi_s$ on the other hand, dimensional analysis shows that the problem is determined by three non-dimensional parameters. One has already been mentioned (the solid volume fraction); the other two can be taken as the density ratio $\rho_p/\rho_f$ and the ratio between gravitational and viscous velocities, $\sqrt{D|g|D/\nu}$. Now, when adding a turbulent background flow to the picture, we introduce at least two additional reference quantities to the problem, namely a fluid velocity scale $u_{ref}$ and a fluid flow length scale $\ell$. Therefore, there will be five independent non-dimensional parameters, the two additional ones being, e.g., a fluid flow Reynolds number $u_{ref}\ell/\nu$ and a length scale ratio $D/\ell$. In the present work we consider fully developed homogeneous-isotropic turbulence as the background flow, implying that the scales of the single-phase flow field can be represented e.g. by the Taylor micro-scale $\lambda$ and the r.m.s. velocity $u_{rms} = \sqrt{2q^2/3}$ (where $q^2 = \int E(\kappa) d\kappa$ is twice the integral of the turbulent kinetic energy, here as evaluated in spectral space over radial wavenumbers $\kappa$).
The problem of settling particles can be characterized by various time-scales: the gravitational scale $\tau_g = \sqrt{D/g}$, the purely viscous scale $\tau_v = D^2/\nu$ and the Stokes drag scale $\tau_p = \rho_p D^2/(\rho_f 18 \nu)$. The background turbulence is often characterized by the Kolmogorov time-scale, $\tau_\eta = \sqrt{\nu/\varepsilon}$, and the large-eddy turnover time $\tau_L = k/\varepsilon$.

These dimensional considerations illustrate the amplitude of the parameter space. It is therefore in general difficult to find reference studies matching a given parameter point. The experiment of Parthasarathy and Faeth (1990) provides one of the most relevant datasets for the present simulations. It provides measurements of fluid and particle data of particles settling in a fluid which is initially at rest, carried out for parameter values mostly comparable to those investigated in the present study, albeit at a much lower solid volume fraction. Their value is approximately $\Phi_s = 10^{-4}$, whereas we are targeting flows with a somewhat higher solid volume fraction of $\Phi_s = 5 \times 10^{-3}$.

The purpose of the present work is to investigate the influence of fluid turbulence upon the settling velocity of solid spherical particles. Contrary to previous studies dealing with single particles fixed in space (e.g. Bagchi and Balachandar 2003; Zeng et al. 2010), our particles are mobile, they are present in large numbers, and the flow is turbulent \textit{a priori}. In order to separate the turbulence effect from the effects of mobility and collectivity, we consider configurations with and without background turbulence.

**Numerical method**

The present simulations have been carried out with the aid of a variant of the immersed boundary technique (Peskin 1972, 2002) proposed by Uhlmann (2005a). This method employs a direct forcing approach, where a localized volume force term is added to the momentum equations. The additional forcing term is explicitly computed at each time step as a function of the desired particle positions and velocities, without recurring to a feedback procedure; thereby, the stability characteristics of the underlying Navier-Stokes solver are maintained in the presence of particles, allowing for relatively large time steps. The necessary interpolation of variable values from Eulerian grid positions to particle-related Lagrangian positions (and the inverse operation of spreading the computed force terms back to the Eulerian grid) are performed by means of the regularized delta function approach of Peskin (1972, 2002). This procedure yields a smooth temporal variation of the hydrodynamic forces acting on individual particles while these are in arbitrary motion with respect to the fixed grid.

Since particles are free to visit any point in the computational domain and in order to ensure that the regularized delta function verifies important identities (such as the conservation of the total force and torque during interpolation and spreading), a Cartesian grid with uniform isotropic mesh width $\Delta x = \Delta y = \Delta z$ is employed. For reasons of efficiency, forcing is only applied to the surface of the spheres, leaving the flow field inside the particles to develop freely.

The immersed boundary technique is implemented in a standard fractional-step method for incompressible flow. The temporal discretization is semi-implicit, based on the Crank-Nicholson scheme for the viscous terms and a low-storage three-step Runge-Kutta procedure for the non-linear part (Verzicco and Orlandi 1996). The spatial operators are evaluated by central finite-differences on a staggered grid. The temporal and spatial accuracy of this scheme are of second order.

The particle motion is determined by the Runge-Kutta-discretized Newton equations for translational and rotational rigid-body motion, which are explicitly coupled to the fluid equations. The hydrodynamic forces acting upon a particle are readily obtained by summing the additional volume forcing term over all discrete forcing points. Thereby, the exchange of momentum between the two phases cancels out identically and no spurious contributions are generated. The analogue procedure is applied for the computation of the hydrodynamic torque driving the angular particle motion.

During the course of a simulation, particles can approach each other closely. However, very thin inter-particle films cannot be resolved by a typical grid and therefore the correct build-up of repulsive pressure is not captured which in turn can lead to possible partial ‘overlap’ of the particle positions in the numerical computation. In practice, we use the artificial repulsion potential of Glowinski et al. (1999), relying upon a short-range repulsion force (with a range of $2\Delta x$), in order to prevent such non-physical situations. Essentially the same method is used for the treatment of particles approaching solid walls.

The present numerical method has been submitted to exhaustive validation tests (Uhlmann 2004, 2005a,b, 2006a), as well as grid convergence studies (Uhlmann 2006b). The computational code has been applied to the case of vertical plane channel flow (Uhlmann 2008).

**Setup of the simulations**

We have performed two different types of numerical experiments. In the first one, particles are released from rest in ambient fluid; the cases realized with this configuration of "pure sedimentation" are denoted as “SA” and “SB”. The second type of configurations features a turbulent background flow, which is homogeneous, (ini-
Table 1: Particle properties. In all cases considered here, particles possess the same relative density with respect to the fluid, viz. $\rho_p/\rho_f = 1.5$, as well as a global solid volume fraction of $\Phi_s = 5 \cdot 10^{-3}$. Two different values for the gravitational acceleration are considered, leading to the following non-dimensional parameters. Note that the particle Reynolds number $Re_{D\infty}$ is based upon the “nominal” settling velocity given by a balance between drag and immersed weight, using the standard drag formula (Clift et al. 1978).

<table>
<thead>
<tr>
<th>cases</th>
<th>$D\sqrt{gD/\nu}$</th>
<th>$Re_{D\infty}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, SA</td>
<td>93.9125</td>
<td>66.53</td>
</tr>
<tr>
<td>B, SB</td>
<td>141.4600</td>
<td>145.85</td>
</tr>
</tbody>
</table>

Table 2: Properties of the initial homogeneous-isotropic flow field.

<table>
<thead>
<tr>
<th>cases</th>
<th>$Re_\lambda$</th>
<th>$k_{max}\eta$</th>
<th>$L_{int}/L_{box}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, B</td>
<td>180.6</td>
<td>0.884</td>
<td>0.0995</td>
</tr>
<tr>
<td>SA, SB</td>
<td>(fluid at rest)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The initial turbulent flow field is generated through spectral simulation of forced homogeneous-isotropic turbulence, using the code of A. Wray (cf. Jiménez and Wray 1998). When the flow has reached a statistically stationary state (verified by monitoring skewness and normalized dissipation rate) a flow field is spectrally interpolated upon the staggered finite-difference grid. The turbulence properties of the single-phase flow are reported in table 2. The actual simulation with the finite-difference code is then started from this initial field (arbitrarily setting the time to zero, $t = 0$), adding particles at random positions and assigning them an initial translational velocity equal to the local fluid velocity. Further pertinent parameter values of the simulations with turbulent background flow are given in table 3. The ratio between the particle diameter and the Kolmogorov length is initially 26.7 (0.85 with respect to the initial Taylor microscale); this ratio then decreases due to turbulence decay, as will be seen below. Concerning the Stokes number, two definitions will be considered. In the first, the particle response time (based on Stokes drag) is divided by the Kolmogorov time scale, viz. $St_T = \tau_p/\tau_T$. In the second definition, the ratio between the same particle time scale and the integral fluid time scale is formed, yielding $St_{int} = \tau_p/T_{int}$. At the time of particle injection, the value of $St_T$ is approximately 60, whereas the value of $St_{int}$ is 2.66.

Table 3: Two-phase flow properties: the following parameters apply to both cases with turbulence background flow (based upon quantities at the initial time $t = 0$).

<table>
<thead>
<tr>
<th>cases</th>
<th>$D/\eta$</th>
<th>$St_T$</th>
<th>$St_{int}$</th>
<th>$\tau_L/\tau_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, B</td>
<td>22.5</td>
<td>59.22</td>
<td>2.66</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The present simulations are realized with $512^3$ grid points. This mesh provides a moderate resolution of initially $\Delta x/\eta = 0.28$ (equivalently $k_{max}\eta = 0.884$) which, however, improves quickly over the course of the simulation. The particles are resolved with $D/\Delta x = 7.5$, which is approximately the same resolution employed by Lucci et al. (2010). The time step is chosen such that the CFL number remains below 0.5.
Results

Figure 1 shows the temporal evolution of the turbulent kinetic energy (TKE) defined as \( k = \langle u_i' u_i' \rangle_f / 2 \) for all four cases. Here and in the following the notation \( \langle \cdot \rangle_f \) is used for spatial averages over the volume occupied exclusively by the fluid. As can be observed from the figure, the overall energy of the fluctuating fluid velocity is only affected at later times by the presence of the particles. In case B, the difference becomes appreciable after approximately 10 particle time units (equivalent to 12 initial large-eddy turnover times \( \tau_L \)), while in case A a difference of only 10% with respect to single-phase flow is measured at \( t/\tau_p = 20 \). As will be discussed below, the initial turbulence intensity is very strong compared to the fluctuations induced by the particle motion. Therefore, the two-phase flow in cases A and B at early times can be considered as nearly one-way coupled, at least as far as kinetic energy is concerned. Conversely, at later times the flow becomes more and more influenced by the presence of particles, and finally the statistics of cases A/SA and B/SB should converge. The figure shows that the asymptotic limit of “pure sedimentation” has not yet been reached in cases A and B by the end of the present runs.

The anisotropy of the fluctuating velocity field can be measured by the anisotropy tensor \( b_{ij} = \langle u_i' u_j' \rangle_f / (2k) - \delta_{ij} / 3 \). Here only the diagonal elements are non-zero, and both horizontal components are identical by symmetry. Therefore only component \( b_{33} \) is shown in figure 2 (the other two being given by \( b_{11} = b_{22} = -b_{33}/2 \)). In both cases without turbulent background flow a value of approximately 0.5 is quickly reached and remains constant. The fluctuations are therefore principally concentrated in the vertical direction (i.e. aligned with the settling velocity). The experimental study of Parthasarathy and Faeth (1990) has likewise shown that sedimenting particles lead to an anisotropic velocity field. In their cases (at low solid volume fractions of \( \Phi_s = 10^{-4} \)), the anisotropy was found to measure \( b_{33} \approx \frac{1}{6} \), at various particle Reynolds numbers (including the present range). With background turbulence, on the other hand, the anisotropy remains initially close to zero and only slowly approaches the strongly anisotropic value obtained in pure sedimentation. The temporal growth of \( b_{33} \) seems to be roughly constant, at least for values of \( b_{33} \leq 1/3 \).

The ratio between the particle diameter and the Kolmogorov length scale, \( \eta = (\nu^3/\varepsilon)^{1/4} \), in cases A, B is shown in figure 3. While the background turbulence decays the Kolmogorov scale grows, leading to a decrease
in time of the relative diameter $D/\eta$. On the figure we can observe that the value is approximately halved over the first five time units. Asymptotically, values of 7 (10) are obtained in cases A (B). This comparison of scales shows that the relative particle size (with respect to the spectrum of turbulent flow scales) varies in time. It should be noted, however, that due to the developing strong anisotropy (favoring the vertical velocity component) the scales will also be highly anisotropic. Their analysis should be performed by means of spatial correlation functions, separately by horizontal/vertical coordinate direction.

The average particle settling velocities $w_{rel}$ are shown (in viscous scaling) in figure 4. This quantity is defined as the difference between the mean velocities of the two phases, viz. $w_{rel} = \langle w_p \rangle_p - \langle w \rangle_f$ ($w_p$ being the vertical component of the particle velocity, $w$ the corresponding fluid velocity component, and the operator $\langle \cdot \rangle_p$ denotes averaging over the number of particles), and it is therefore in general different from the average over the relative velocities seen by each particle. Fundamental differences between cases A, B on the one hand and cases SA, SB on the other hand can be observed from the figure. Firstly, the initial mean acceleration due to gravity is much smaller in the turbulent cases. The difference diminishes with time and after $t/t_p = 7$ (12) in cases A/SA (B/SB) a cross-over takes place, after which the particles settle on average faster in the turbulent environment. The relative difference in settling velocity between cases A and SA is approximately 4% at times larger than 20 particle time units; for cases B, SB the relative difference amounts to 1% (cf. figure 5). Although the long-time difference is relatively small, it is systematic, and we therefore consider it as physical, especially between cases A and SA.

Let us first discuss the different short time behavior. One possible mechanism acting to decrease the mean settling velocity is the well-known non-linear drag effect (Crowe et al. 1998). Although experiments show considerable scatter, the general view is that turbulent fluctuations of the velocity seen by the particles together with the non-linearity of the drag law lead to an increase of the mean drag coefficient, and therefore a decrease in settling velocity. Since the turbulence intensity is initially very strong, the non-linearity of the drag can be expected to play a significant role at short times. However, the argument hinges on the knowledge of (i) a drag law with instantaneous validity, and (ii) the precise definition of a relative velocity (cf. discussion in Bagchi and Balachandar 2004). In fact, Bagchi and Balachandar (2004) did not observe any systematic effect of turbulence upon the mean drag.

Concerning the long-time behavior, it should be remarked that the apparent persistence of the effect of the initial background turbulence is somewhat surprising. It seems that the small residual turbulent agitation is causing the particles to fall faster than in the pure sedimentation cases. The principal mechanism known to lead to faster settling velocities under turbulent conditions is the preferential sweeping mechanism (Wang and Maxey 1993), which, however, has thus far only been confirmed for very small particles. In order to test the possibility of preferential particle trajectories in the present cases, conditional sampling of fluid quantities along particle trajectories needs to be performed.

Figure 6 depicts the ratio between the square root of the turbulence intensity ($u_{rms} = \sqrt{2k}$) and the instantaneous average settling velocity, viz. $I = u_{rms}/w_{rel}$.
Figure 7: The temporal evolution of the average dissipation rate normalized by the initial value $\varepsilon_0$, shown for case A (---) and case B (--). The result for single phase flow is shown in blue.

The quantity $I$ is a measure of the relative intensity of particle-induced flow structures (i.e. wakes) as compared to velocity fluctuations attributed to the turbulent background flow. Its value in the present cases A and B is initially very large (in fact it has a singularity at the origin since particles are at rest), dropping to values below unity by $t/t_{ref} \approx 4$ (2) in case A (B). The difference between the curves corresponding to the two cases A and B reflects the fact that the respective settling velocities differ by roughly a factor of two. The temporal decay of the parameter $I$ in cases A and B implies that these simulations encompass the whole spectrum of relative turbulence intensities from very strong agitation (early times) to the limit of purely particle-induced fluctuations (long times). In fact, figure 6 shows that the asymptotic value of the parameter $I$ in both pure sedimentation cases SA, SB is approximately 0.08, independent of the particle Reynolds number. It can also be seen that at the end of the observation interval discussed here, cases A, B have not yet reached the regime of pure sedimentation, with values of $I$ still between 1.5 and 2 times larger than the counterparts without initial background turbulence.

The dissipation rate of turbulent kinetic energy is shown in figure 7. Visibly, the addition of particles is causing an increase of energy dissipation. This is expected since each particle introduces additional gradients near its surface, thereby dissipating kinetic energy. In the present cases, however, the additional dissipation is offset by additional generation of kinetic energy due to the work the particles exert on the fluid, as evident from figure 1 discussed above. Concerning the difference in dissipation between cases A and B, an approximate factor of 8 separates the two curves at large times ($t/t_{p} \geq 30$). When considering that the average particle settling velocities of these two cases differ by a factor of 2.2, it appears that the average dissipation rate (when the background turbulence has already sufficiently decayed) is roughly proportional to the third power of the settling velocity.

In order to quantify the location of regions where additional dissipation is acting, we have averaged the dissipation rate over spherical shells between a radial distance $\rho = D/2$ (the particle surface) and an outer radius $\rho = R$, viz.

$$\langle \varepsilon \rangle_s = \frac{1}{\rho_s V_s} \int_{D/2}^{R} \int_{0}^{2\pi} \int_{0}^{\pi} \varepsilon \, d\phi \, d\psi \, d\rho,$$

where $V_s$ is the settling velocity of the particle.
Figure 9: Vorticity magnitude in case A, showing a vertical slice at three different instants: \( t/\tau_p = 0.14, 1.92, 10.35 \) (from top to bottom).

where \( V_s = \int_{D/2}^{R} \int_0^{2\pi} \int_0^\pi d\phi d\psi d\rho \) is the volume of the shell. In figure 8 the quantity \( \langle \varepsilon \rangle_s \) is shown as a function of the outer shell radius \( R \) for different instants in time in cases A and B. It can be seen that dissipation is indeed much larger than average near the particle surfaces, decreasing towards unity with distance from the particle. The local values increase in time relative to the box-average dissipation since turbulence decays in time, i.e. the dissipation rate becomes more and more localized around the particles. When plotted in log-log scale (not shown), it becomes obvious that the dissipation rate decays as a power-law \( R^{-n} \) for short distances. Specifically, the measured radial decay rates for the three curves in figure 8 are \( n = 0.4, 2.2 \) and 2.5 (with increasing time).

Snapshots of the flow field of case B at different instants are shown in figure 9. The visualization of the vorticity magnitude in vertical slices demonstrates how vortical structures in the neighborhood of the particles (located above the particle location) are nearly invisible at early times, and then progressively start to occupy the stage. In the final state \( (t/\tau_p = 10.35) \) the vorticity field is visibly dominated by wakes. A further analysis of the properties of wakes behind collectively sedimenting particles as well as the implications for the turbulence spectra would be desirable.

In order to describe the spatial distribution of the dispersed phase, we determine the average distance between nearest neighbors, defined as follows:

\[
d_{\text{min}} = \frac{1}{N_p} \sum_{i=1}^{N_p} \min_{j \neq i}(d_{i,j}),
\]

\[
d_{\text{min}} = \frac{1}{N_p} \sum_{i=1}^{N_p} \sum_{j=1}^{N_p} \min_{j \neq i}(d_{i,j}),
\]

where \( d_{i,j} = |x_c^{(i)} - x_c^{(j)}| \) is the distance between the centers of particles \( i \) and \( j \). In figure 10 the quantity \( d_{\text{min}} \) is normalized by the value of particles distributed on a cubical lattice \( d_{\text{hom}} = (V_\Omega/N_p)^{1/3} \) (where \( V_\Omega \) is the volume of the computational domain). It can be seen that without background turbulence the distance to the nearest neighbor is somewhat larger than with turbulence (approximately 0.65 compared to 0.58). The turbulent cases A, B exhibit values which are initially very close to a random distribution, similar to findings in vertical turbulent channel flow (Uhlmann 2008). At later times the values of \( d_{\text{min}} \) in cases A, B tend slowly towards the asymptotic value reached in pure sedimentation. This result implies that the initial strong turbulence maintains an approximately random spatial distribution.
Probability density functions (pdfs) of particle velocity and hydrodynamical force components acting on the particles are shown in figure 11. The pdfs are normalized in order to study their shape independently of the mean value and the standard deviation. The figure shows data for case B at $t/\tau_p \approx 24$, averaged over a short interval of $\Delta T/\tau_p = 4.4$. We observe that all velocity components behave nearly Gaussian (both horizontal components should be equal by symmetry, which provides a measure of the quality of the statistics). On the other hand, the pdfs of the particle forces, which – under this normalization – are identical to the particle acceleration statistics, exhibit a clear deviation from Gaussianity. Firstly, the horizontal components are still symmetric (as they should be due to symmetry), but have longer tails than the Gaussian reference curve. Secondly, the vertical force component is markedly asymmetric with a visible positive skewness. It should be noted that the force statistics have been filtered such that data from particles which are instantaneously “in contact” (i.e. those which are within the range of the artificial repulsion force) have been removed from the dataset. Now, a positive fluctuation $F_z'$ implies an instantaneous fluctuation which is directed upward. A positive skewness of $F_z'$ could be generated by a non-linear drag effect. If one assumes that the drag is quasi-steady (i.e. instantaneously given by the standard drag law), and the characteristic relative flow velocity has a symmetric pdf, then the non-linearity of the velocity/drag-force relation would indeed lead to a positively skewed pdf for the force. A positive skewness of the pdf for the vertical force has also been observed in the case of vertical channel flow (unpublished data from the simulation of Uhlmann 2008). This persistent result merits further investigation in the future.

**Conclusions**

We have simulated the settling of spherical particles at moderate Reynolds numbers and low solid volume fractions. The solid/fluid interfaces were fully resolved by means of an immersed boundary method. Two spatially homogeneous configurations were investigated: pure sedimentation in ambient fluid and sedimentation with decaying turbulent background flow.

The results show that turbulence initially leads to a significant decrease in the mean settling velocity. For large times, however, particles settle on average slightly more rapidly in turbulent flow. Our analysis of the spatial distribution of particles has revealed that the particles are more evenly distributed in the cases of pure sedimentation. This effect is small, but clearly noticeable from the average distance to the nearest neighbor.

It was found that particle velocity pdfs are close to a Gaussian function, but hydrodynamic particle forces possess wider tails. Interestingly, the pdf of the force component in the vertical direction exhibits a positive skewness.

The effect of particles upon the fluid turbulence is only felt at later times, when the initial background turbulence has already sufficiently decayed. The two-way coupling effect is such that turbulent kinetic energy and average dissipation rate are both enhanced. The later quantity was shown to be more and more localized around the particles. Moreover, anisotropy is generated
such that the vertical fluctuations are strongly enhanced. In the future the current results will first be verified at a higher spatial resolution. It is planned to investigate in more detail the effect of the size of the computational domain upon the results, especially in the vertical direction. We will then turn to higher particle Reynolds numbers, with the purpose of studying possible cluster formation through wake attraction.

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