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An experimental study on the settling velocity of inertial particles in different homogeneous isotropic turbulent flows

Amélie Ferran^{1, 2}†, Nathanaël Machicoane¹, Alberto Aliseda², Martín Obligado¹

¹Univ. Grenoble Alpes, CNRS, Grenoble-INP, LEGI, F-38000 Grenoble, France

²Department of Mechanical Engineering, University of Washington, Seattle, Washington 98195-2600, USA

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We propose an experimental study on the gravitational settling velocity of dense, sub-Kolmogorov inertial particles under different background turbulent flows. We report Phase Doppler Particle Analyzer measurements in a low-speed wind tunnel uniformly seeded with micrometer scale water droplets. Turbulence is generated with three different grids (two consisting on different active-grid protocols while the third is a regular static grid), allowing us to cover a very wide range of turbulence conditions in terms of Taylor-scale based Reynolds numbers ($Re_\lambda \in [30 - 520]$), Rouse numbers ($Ro \in [0 - 5]$) and volume fractions ($\phi_v \in [0.5 \times 10^{-5} - 2.0 \times 10^{-5}]$).

We find, in agreement with previous works, that enhancement of the settling velocity occurs at low Rouse number, while hindering of the settling occurs at higher Rouse number for decreasing turbulence energy levels. The wide range of flow parameters explored allowed us to observe that enhancement decreases significantly with the Taylor Reynolds number and is significantly affected by the volume fraction ϕ_v . We also studied the effect of large-scale forcing on settling velocity modification. The possibility of change the inflow conditions by using different grids allowed us to test cases with fixed Re_λ and turbulent intensity but different integral length scale. Finally, we assess the existence of secondary flows in the wind tunnel and their role on particle settling. This is achieved by characterising the settling velocity at two different positions, the centreline and close to the wall, with the same streamwise coordinate.

Key words:

† Email address for correspondence: amelie.ferran1@univ-grenoble-alpes.fr

32 1. Introduction

33 Turbulent flows laden with particles are present in both environmental phenom-
 34 ena and industrial applications. For instance, water droplets, snowflakes and
 35 pollutants in atmospheric turbulence, sediments in rivers and industrial sprays
 36 all involve turbulent environments carrying inertial particles (Crowe *et al.* (1996);
 37 Shaw (2003); Monchaux *et al.* (2012); Li *et al.* (2021)). Inertial particles do not
 38 follow the fluid velocity field as tracers, having their own dynamics that depend
 39 on both their finite size and their density ratio compared to that of the carrier
 40 phase.

41 Two phenomena resulting from the influence of turbulence on the motion
 42 of inertial particles have been widely studied: preferential concentration and
 43 modification of the settling velocity. Preferential concentration refers to the fact
 44 that an initially uniform or random distribution of particles will form areas of
 45 clusters and voids (Maxey (1987); Squires & Eaton (1991); Aliseda *et al.* (2002);
 46 Obligado *et al.* (2014); Sumbekova *et al.* (2017)) due to the accumulation in
 47 certain regions of the turbulent flow where the hydrodynamic forces exerted by
 48 the flow tend to drive the particles. Furthermore, settling velocity modification
 49 occurs when particles immersed in a turbulent flow have their settling speed V_s
 50 altered compared to that in a stagnant fluid or laminar flow V_T (Wang & Maxey
 51 (1993); Crowe *et al.* (1996); Aliseda & Lasheras (2011)). These two features of
 52 turbulent-laden flow are known to be linked together as the settling velocity of
 53 a particle can be increased due to an increase of the particle local concentration
 54 (Aliseda *et al.* (2002); Gustavsson *et al.* (2014); Huck *et al.* (2018)).

55 Regarding the modification of the settling velocity, multiple experimental and
 56 numerical studies have shown that turbulence can both hinder ($V_s < V_T$) or
 57 enhance the particle settling velocity ($V_s > V_T$). While several studies have re-
 58 ported enhancement of the settling velocity (Wang & Maxey (1993); Aliseda *et al.*
 59 (2002); Bec *et al.* (2014); Rosa *et al.* (2016)), others show evidence of hindering
 60 only (Akutina *et al.* (2020); Mora *et al.* (2021)) or of both types of modification
 61 (Nielsen (1993); Good *et al.* (2012); Sumbekova *et al.* (2016); Monchaux & Dejoan
 62 (2017); Petersen *et al.* (2019); Falkinoff *et al.* (2020); Reartes & Mininni (2021)).
 63 While the nature and number of mechanisms controlling this phenomenon is still a
 64 matter of debate, several models have been proposed in the literature, sometimes
 65 even giving contradictory predictions.

66 Enhancement of the settling velocity can be explained by the preferential
 67 sweeping mechanism, also known as fast-tracking effect, where inertial particles
 68 tend to spend more time in downwards moving regions of the flow than in upwards
 69 flow (Wang & Maxey (1993)). Some mechanisms have been proposed as well to
 70 explain hindering. The vortex trapping effect describes how light particles can be
 71 trapped inside vortices (Nielsen (1993); Aliseda & Lasheras (2006)). The loitering
 72 mechanism assumes that falling particles spend more time in upward regions of
 73 the flow than downward regions (Chen *et al.* (2020)), while a nonlinear drag can
 74 also explain that particles are slowed down in their fall by turbulence (Good
 75 *et al.* (2014)). Models have been developed to estimate the influence of clustering
 76 and particle local concentration on the settling rate enhancement (Alipchenkov
 77 & Zaichik (2009); Huck *et al.* (2018)).

78 However, even in the simplified case of small, heavy particles in homogeneous
 79 isotropic turbulence (HIT) no general consensus has been found on the influence of
 80 turbulence, through the Taylor-Reynolds number Re_λ , on the transition between

81 hindering and enhancement. $Re_\lambda = u' \lambda / \nu$ is based on the Taylor microscale λ
 82 where u' and ν are the carrier phase rms (root-mean-square) of the fluctuating
 83 velocity and kinematic viscosity, respectively. The influence of Re_λ on the maxi-
 84 mum of enhancement, i.e. when $V_s - V_T$ reaches its maximum, is also still under
 85 debate. Depending on the range of Re_λ , some studies found that the maximum
 86 enhancement increases with Re_λ (Nielsen (1993); Yang & Lei (1998); Bec *et al.*
 87 (2014); Rosa *et al.* (2016); Wang *et al.* (2018)), whereas other studies show the
 88 opposite trend (Mora *et al.* (2021)). Furthermore, a non-monotonic behaviour
 89 of $\max(V_s - V_T)$ with Re_λ has also been reported (Yang & Shy (2021)), where
 90 $\max(V_s - V_T)$ corresponds to the maximal settling velocity with respect to the
 91 terminal velocity, with both V_s and V_T being functions of the particle size.

92 Several non-dimensional parameters have been found to play a role on the
 93 settling velocity. The dispersed phase interactions with turbulent structures are
 94 characterised by the Stokes and Rouse numbers (Maxey (1987)), whereas the
 95 magnitude of turbulence excitation is quantified by the Taylor Reynolds number.
 96 The Stokes number, describing the tuning of particle inertia to turbulent eddies
 97 turn over time, is defined as the ratio between the particle relaxation time and
 98 a characteristic timescale of the flow $St = \tau_p / \tau_k$, where τ_k has been shown to be
 99 represented by the Kolmogorov time scale τ_η . The Rouse number - also known
 100 as Sv - is a ratio between the particle terminal speed and the velocity scale of
 101 turbulence fluctuations, in this case the turbulent velocity rms, $Ro = V_T / u'$.
 102 Hence, it is a competition between turbulence and gravity effects. While all
 103 these parameters are relevant for modelling and understanding the interactions
 104 of inertial particles and turbulence, there are still no consensus even on the set
 105 of non-dimensional numbers required to do so. Furthermore, the determination
 106 of length and time flow scales relevant to the settling speed modification has also
 107 been the subject of significant discussion in the literature. Yang & Lei (1998)
 108 determined that a mixed scaling using both τ_η and u' appears to be an appropriate
 109 combination of parameters for the present problem. There is a general agreement
 110 that the modification of the settling velocity is a process that encompass all
 111 turbulent scales and, consistent with even single-phase HIT, a single flow scale
 112 is not sufficient to completely describe it. It has been shown that the particle
 113 settling velocity is affected by larger flow length scales with increasing Stokes
 114 number (Tom & Bragg (2019)).

115 Experimentally, the influence of turbulence on the particle settling velocity has
 116 been studied in an air turbulence chamber (Petersen *et al.* (2019) Good *et al.*
 117 (2014)), channel flows (Wang *et al.* (2018)), Taylor Couette flows (Yang & Shy
 118 (2021)), water tank with vibrating-grids turbulence (Yang & Shy (2003); Poelma
 119 *et al.* (2007); Zhou & Cheng (2009); Akutina *et al.* (2020)) and wind tunnel
 120 turbulence (Aliseda *et al.* (2002); Sumbekova *et al.* (2017); Huck *et al.* (2018);
 121 Mora *et al.* (2021)). However, measuring the particle settling velocity in confined
 122 flows, such as in a wind tunnel, can be challenging due to the recirculation
 123 currents that may arise on the carrier phase. Weak carrier phase currents in
 124 the direction of gravity can be of the order of the smallest particle velocity and
 125 impact significantly the measurements of the settling velocity, (as reported in
 126 Good *et al.* (2012); Sumbekova (2016); Wang *et al.* (2018); Akutina *et al.* (2020);
 127 Mora *et al.* (2021); Pujara *et al.* (2021); De Souza *et al.* (2021)). Akutina *et al.*
 128 (2020) dealt with this bias by removing the local mean fluid velocity from the
 129 particle instantaneous velocity measurements.

130 Accurate measurements of settling velocity and the local properties of the
131 carrier-phase flow are therefore one aspect of major importance to better un-
132 derstand the role of turbulence on settling velocity modification. This work
133 studies the settling velocity of sub-Kolmogorov water droplets in wind tunnel
134 grid-generated turbulence. Turbulence is generated with three different grids (two
135 consisting on different active-grid protocols while the third is a regular static
136 grid), allowing us to cover a very wide range of turbulence conditions, with the
137 turbulence intensity u'/U_∞ ranging from 2 to 15%, $Re_\lambda \in [34, 520]$ and integral
138 length scales $\mathcal{L} \in [1, 15]$ cm.

139 Particle settling velocity and diameter were quantified using a Phase Doppler
140 Particle Analyzer (PDPA), as described in a previous work on the same facility
141 (Mora *et al.* (2021); Mora (2020)). Our experimental setup has three unique
142 features that contribute to the novelty of our results. First, the resolution of
143 the particle vertical velocity is a factor of 10 higher than in Mora *et al.* (2021).
144 This higher resolution enables the study of the settling velocity of particles with
145 very small inertia, as small as $1 \mu\text{m}$, corresponding to the range where settling
146 is enhanced. Furthermore, thanks to the increased resolution in the vertical
147 velocity, we can assess the existence of secondary flows in the wind tunnel by
148 analysing the carrier flow vertical velocity with the Cobra probe and the PDPA
149 velocity of tracer particles. We measure the settling velocity at two different
150 positions, the centreline and near the sidewalls, for the same streamwise location.
151 Additionally, we perform measurements of the single-phase velocity with a Cobra
152 probe, a multi-hole pitot tube that resolves the average and rms values of the
153 3D velocity vector (Obligado *et al.* 2022), that allows the quantification of small
154 inhomogeneities in the single-phase flow, for all turbulent conditions studied.
155 We find that the vertical velocity measured in dilute two-phase conditions is
156 consistent with such inhomogeneities. For larger values of volume fraction, the
157 vertical velocities become a non-trivial function of position, streamwise veloc-
158 ity and particle loading. This work, therefore, gives quantitative experimental
159 evidence of the role and relevance of inhomogeneities and recirculation in the
160 quantification of the settling velocity in confined domains.

161 Finally, the generation of turbulence with three different methods allows us
162 to explore experimental realisations with similar values of Re_λ and u'/U_∞ but
163 significantly different values of \mathcal{L} (a factor 2 different). This allows us to disen-
164 tangle the role of the large turbulent scales on settling velocity modification,
165 opening the door to expand available models to non-homogeneous flows. To
166 the authors' best knowledge, our work presents the first experimental evidence
167 capable of discriminating between the influence of large and small turbulent scales
168 on particle settling. This is relevant not only for real-world physics, but also to
169 learn from different laboratory setups and numerical simulations, as the ratio
170 of small to large scales is different in each of these studies. In consequence,
171 the present work is unique as it covers a broad range of turbulent flows, while
172 resolving the settling velocity of particles as small as $1 \mu\text{m}$. These measurements
173 were complemented by hot-wire anemometry, that resolves all scales of the flow
174 for the three turbulent conditions studied.

175 The paper is organised as follows. Section 2 describes the experimental setup
176 with the generation of turbulence, the injection of inertial particles and the PDPA
177 misalignment correction. Section 3 presents the experimental results, with first
178 the raw data and the presence of secondary currents. The influence of Re_λ , others

179 non-dimensional numbers on the settling velocity and a scaling of the maximum of
 180 enhancement is then displayed. Re_λ is shown to have a non-monotonic influence
 181 on the settling enhancement. We found that the integral length scale have an
 182 influence on the settling velocity even for very low Stokes number. Section 4
 183 presents the influence of the turbulent flow large scales on the settling velocity.
 184 Finally, section 6 summarises the results and draws conclusions.

185 2. Experimental setup

186

2.1. Grid Turbulence in the Wind Tunnel

187 Experiments were conducted in the Lespinard wind tunnel, a closed-circuit wind
 188 tunnel at LEGI (Laboratoire des Ecoulements Géophysiques et Industriels),
 189 Grenoble, France. The test section is 4 m long with a cross section of
 190 $0.75\text{ m} \times 0.75\text{ m}$. A sketch of the facility is shown in the panel of Figure 1a.
 191 The turbulence is generated with two different grids: a static (regular) and an
 192 active grid. The regular grid (RG) is a passive grid composed by 7 horizontal
 193 and 7 vertical round bars forming a square mesh with a mesh size of 10.5 cm.
 194 The active grid is composed by 16 rotating axes (eight horizontal and eight
 195 vertical) mounted with co-planar square blades and a mesh size of 9 cm, (see
 196 Obligado *et al.* (2011); Mora *et al.* (2019b) for further details about the active
 197 grid). Each axis is driven by a motor whose rotation rate and direction can be
 198 controlled independently. Two protocols were used with the active grid. In the
 199 active grid (AG) protocol -also referred to as “triple-random” in the literature
 200 (Johansson (1991); Mydlarski (2017))- the blades move with random speed and
 201 direction, both changing randomly in time, with a certain time scale provided
 202 in the protocol. For the open-grid protocol (OG), each axis remains completely
 203 static with the grid fully open, minimising blockage. These two protocols have
 204 been shown to create a large range of turbulent conditions, from $Re_\lambda \sim 30$ for
 205 OG to above 800 for AG (Mora *et al.* (2019b); Obligado *et al.* (2020)).

206 The turbulent intensity u'/U_∞ obtained for OG is in the same range as for RG
 207 ($\approx 2 - 3\%$). The turbulent intensity created by the AG is much larger, just below
 208 15%. However, some significant differences exist between RG and OG turbulence:
 209 the bar width of the regular grid is twice that of the open grid (2 cm vs. 1 cm) and
 210 the open grid has a 3D structure due to the square blades (see Figure 1b for an
 211 illustration of the OG). This implies significant differences in the integral length
 212 scale \mathcal{L} of the turbulence, $\approx 6\text{ cm}$ for RG versus $\approx 3\text{ cm}$ for RG. These various
 213 grid configurations allowed us to explore different Taylor-scale Reynolds numbers
 214 Re_λ , from 34 to 513 at a fixed freestream velocity. Additionally, our experimental
 215 setup allowed for the study of particles at similar values of u'/U_∞ and Re_λ , but
 216 different \mathcal{L} (with OG versus RG). Matching the AG Reynolds number with the
 217 passive grids was not possible as it would require high wind tunnel velocities in
 218 the RG/OG cases, which would limit the measurements of the settling velocity
 219 due to low resolution.

220 Hot-wire anemometry (HWA) measurements were taken to characterise the
 221 single-phase turbulence (Mora *et al.* (2019b)). A constant temperature anemome-
 222 ter (Streamline, Dantec Inc.) was used with a 55P01 hot-wire probe (5 μm in
 223 diameter, 1.25 mm in length). The hot-wire was aligned with the centreline
 224 of the tunnel, (3 m downstream the turbulence generation system). Additional
 225 measurements were carried out near the wall of the wind tunnel to check the

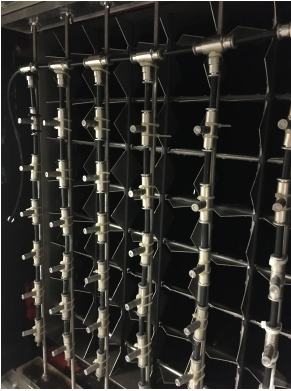
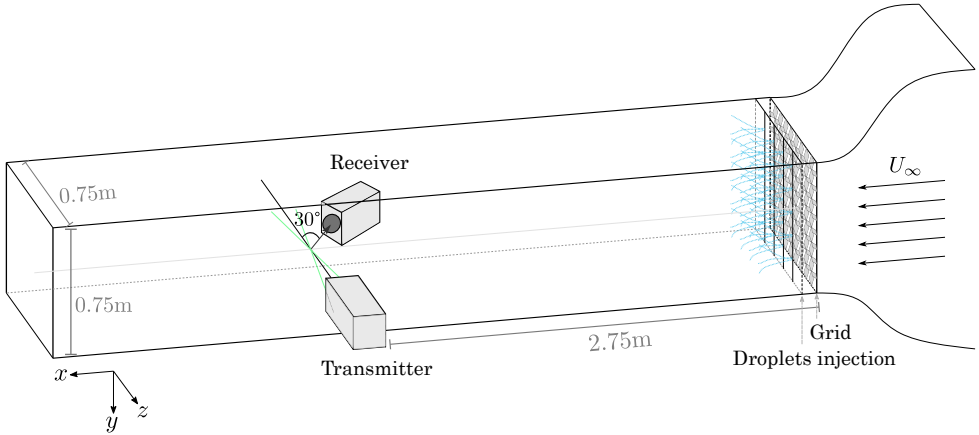
226 homogeneity of the turbulence characteristics. Velocity time series were recorded
 227 for 180 s with a sampling frequency F_s of 50 kHz. This sampling frequency
 228 provides adequate resolution down to the Kolmogorov length scale η .

229 The background flow was also characterised with a Cobra Probe: a multi-
 230 hole pressure probe which is able to capture three velocity components. This
 231 multi-hole pitot tube probe (Series 100 Cobra Probe, Turbulent Flow Instrument
 232 TFI, Melbourne, Australia) was used to characterise possible contributions of
 233 the non-streamwise velocity components to the average value. Weak secondary
 234 motions in the carrier phase can arise in two-phase flow conditions due to the fall
 235 of inertial particles, as we will see in section 3.2, and in single phase condition
 236 due to confinement effects. The Cobra probe was used in this study to estimate
 237 the mean vertical flow for the latter. The acquisition time of the measurements
 238 was set to 180 s with a data rate of 1250 Hz (the maximum attainable). As the
 239 turbulence scales may reach beyond this frequency, and may not be resolved
 240 due to the finite size of the probe, which has a sensing area of 4 mm^2 (Mora
 241 *et al.* (2019b); Obligado *et al.* (2022)), these measurements are used only to
 242 compute the mean and rms values of the 3D velocity vector. To estimate the
 243 small angle present between the probe head and the direction of the mean flow,
 244 measurements were collected in laminar flow conditions (i.e, without any grid in
 245 the test section), to estimate the misalignment angle between the Cobra head
 246 and the streamwise direction.

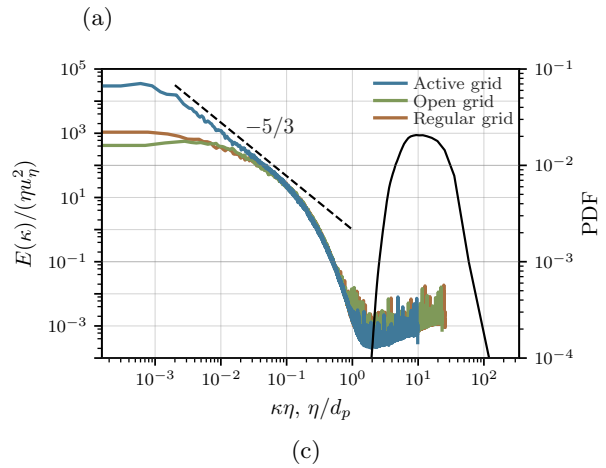
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248 Single-point turbulence statistics were calculated for each flow condition. The
 249 turbulent Reynolds number based on the Taylor microscale is defined as $Re_\lambda =$
 250 $u' \lambda / \nu$ where u' is the standard deviation of the streamwise velocity component,
 251 ν the kinematic viscosity of the flow and λ the Taylor microscale. The Taylor mi-
 252 croscale was computed from the turbulent dissipation rate ε with $\lambda = \sqrt{15\nu u'^2 / \varepsilon}$,
 253 extracted as $\varepsilon = \int 15\nu \kappa^2 E(\kappa) d\kappa$ where $E(\kappa)$ is the energy spectrum along the
 254 wavenumber κ . The small scales of the turbulent flow are characterised by the
 255 Kolmogorov length, time and velocity scales: $\eta = (\nu^3 / \varepsilon)^{1/4}$, $\tau_\eta = (\nu / \varepsilon)^{1/2}$ and
 256 $u_\eta = (\nu \varepsilon)^{1/4}$. Different methods were used to estimate the integral length scale. \mathcal{L}
 257 was first computed by direct integration of the autocorrelation function until the
 258 first zero-crossing $\mathcal{L}_a = \int_0^{\rho_\delta} R_{uu}(\rho) d\rho$ and until the smallest value of ρ for which
 259 $R_{uu}(\rho_\delta) = 1 / \exp$ (Puga & Larue (2017); Mora *et al.* (2019b)). The integral length
 260 scale was also estimated from a Voronoï analysis of the longitudinal fluctuating
 261 velocity zero-crossings \mathcal{L}_{voroi} , following the method recently proposed in (Mora &
 262 Obligado (2020)), where an extrapolation of the 1/4 scaling law was performed
 263 when needed. The latter is particularly relevant for the active grid mode, where
 264 the value of R_{uu} has been found, in some cases, to not cross zero (Puga & Larue
 265 (2017)). The estimation of \mathcal{L} using $\mathcal{L} = C_\varepsilon u'^3 / \varepsilon$ was not used in this study as the
 266 prefactor C_ε is not fixed for different turbulent conditions (i.e. different grids).

267 Table 1 summarises the flow parameters for all experimental conditions studied.
 268 The right panel of Figure 1c shows the power spectral density of the streamwise
 269 velocity computed from hot-wire time signals at the measurement location ($x \approx$
 270 3 m for all cases). The three spectra depicted in the figure were obtained
 271 from the three different grid configurations, all of them with an inlet velocity
 272 of approximately 4 m/s . The power spectral density was normalised by the
 273 Kolmogorov length and velocity scales η and u_η . As expected, the turbulent flow



(b)



(c)

Figure 1: (a) Sketch of the wind tunnel with the PDPA measurement system. (b) Picture of the droplet injection system and, behind it, of the active grid in open grid mode. (c) Power spectral density of the longitudinal velocity from hot-wire records normalised by the Kolmogorov scale for an inlet velocity around 4 m/s. The dashed line presents a Kolmogorov $-5/3$ power law scaling, as reference. The inertial particle diameter distribution averaged over all the experiments and normalised by the Kolmogorov scale is shown on the right axis. Note that it is plotted against η/d_p .

274 generated by the active grid exhibits a considerably wider inertial range. On the
 275 right of the figure, for large values of $\kappa\eta$, the diameter distribution averaged over
 276 all the experiments is displayed. The diameter distribution, discussed in the next
 277 section, was normalised by the smallest Kolmogorov scale among all conditions
 278 (i.e. the Kolmogorov scale of the active grid turbulent flow). It can be observed
 279 that the distribution is polydisperse and particles are always much smaller than
 280 the Kolmogorov scale of the turbulence. Figure 2 shows the Taylor Reynolds
 281 number Re_λ and the Taylor microscale λ for different wind tunnel velocities 3 m
 282 downstream (at approximately $x/M \approx 30$).

Parameters	AG	OG	RG
U_∞ (ms^{-1})	2.6 - 5.0	2.6 - 5.0	2.6 - 5.0
Re_λ	268 - 513	34 - 55	49 - 68
u'/U_∞ (%)	13.2 - 14.9	1.9 - 2.1	2.5 - 2.7
$10^3 \times \varepsilon$ ($m^2 s^{-3}$)	140.1 - 1251.4	6.9 - 26.8	9.9 - 59.5
η (μm)	230 - 406	634 - 868	511 - 792
τ_η (ms)	3.5 - 11.0	26.7 - 50.2	17.4 - 41.9
λ (cm)	1.02 - 1.29	0.92 - 1.16	0.83 - 1.09
\mathcal{L}_{a0} (cm)	16.3 - 22.4	3.0 - 3.1	5.5 - 8.7
$\mathcal{L}_{a\delta}$ (cm)	8.5 - 9.6	1.8 - 1.9	2.2 - 2.4
\mathcal{L}_{voro} (cm)	14.0 - 24.0	2.3 - 2.8	3.7 - 4.5

Table 1: Turbulence parameters for the carrier phase, sorted by grid category computed from hot-wire anemometry measurements 3 meters downstream of the grid. U_∞ is the freestream velocity, u' the rms of the streamwise velocity fluctuations, $Re_\lambda = u'\lambda/\nu$ the Taylor-Reynolds number and $\varepsilon = 15\nu u'^2/\lambda^2$ the turbulent energy dissipation rate. $\eta = (\nu^3/\varepsilon)^{1/4}$ and $\tau_\eta = (\nu/\varepsilon)^{1/2}$ are the Kolmogorov length and time scales. $\lambda = \sqrt{15\nu u'^2/\varepsilon}$ and \mathcal{L} are the Taylor microscale and the integral length scale, respectively, where three different methods are used to compute \mathcal{L} .

283

2.2. Particle Injection

284 Water droplets were injected in the wind tunnel by means of a rack of 18 or 36
285 injectors distributed uniformly across the cross-section. The outlet diameter of the
286 injectors is of 0.4 mm, and atomization is produced by high-pressure at 100 bars.
287 The water flowrate introduced in the test-section by the droplet injection system
288 was measured with a flow meter for each experiment and varied between 0.5 and
289 3.4 l/min. The air flowrate in the tunnel was computed using the measured mean
290 streamwise velocity and the cross-sectional area. The particle volume fraction
291 $\phi_v = F_{water}/F_{air}$ describes the ratio between the liquid and air volumetric
292 flowrates. With the range of liquid flowrates and air velocities used in the
293 experiments, the volume fraction ϕ_v varied between $\phi_v \in [0.5 \times 10^{-5}, 2.0 \times 10^{-5}]$.
294 18 or 36 injectors were used depending on the experimental conditions, as low
295 volume fractions could not be reached with 36 injectors. The resulting inertial
296 water droplets have a polydisperse size distribution with a D_{max} and D_{32} of
297 $\approx 30 \mu m$ and $\approx 65 \mu m$, respectively (Sumbekova *et al.* (2017)), as shown in
298 Figure 1c, with D_{32} the Sauter mean diameter. The droplet Reynolds numbers
299 Re_p are smaller than one. For each grid mode, three different volume fraction
300 were tested, with three different freestream velocities ($U_\infty = 2.6, 4.0, 5.0$ m/s).
301 This results in 27 different experimental conditions.

302

303 Measurements were collected with a Phase Doppler Analyzer (PDPA) (Bachalo
304 & Houser (1984)). The PDPA (PDI-200MD, Artium Technologies) is composed
305 of a transmitter and a receiver positioned at opposite sides of the wind tunnel.
306 The transmitter emits two solid-state lasers, green at 532 nm wavelength and
307 blue at 473 nm wavelength. Both lasers are split into two beams of equal intensity
308 and one of these is shifted in frequency by 40 MHz, so that when they overlap
309 in space they form an interference pattern. The 532 nm beam enables us to take

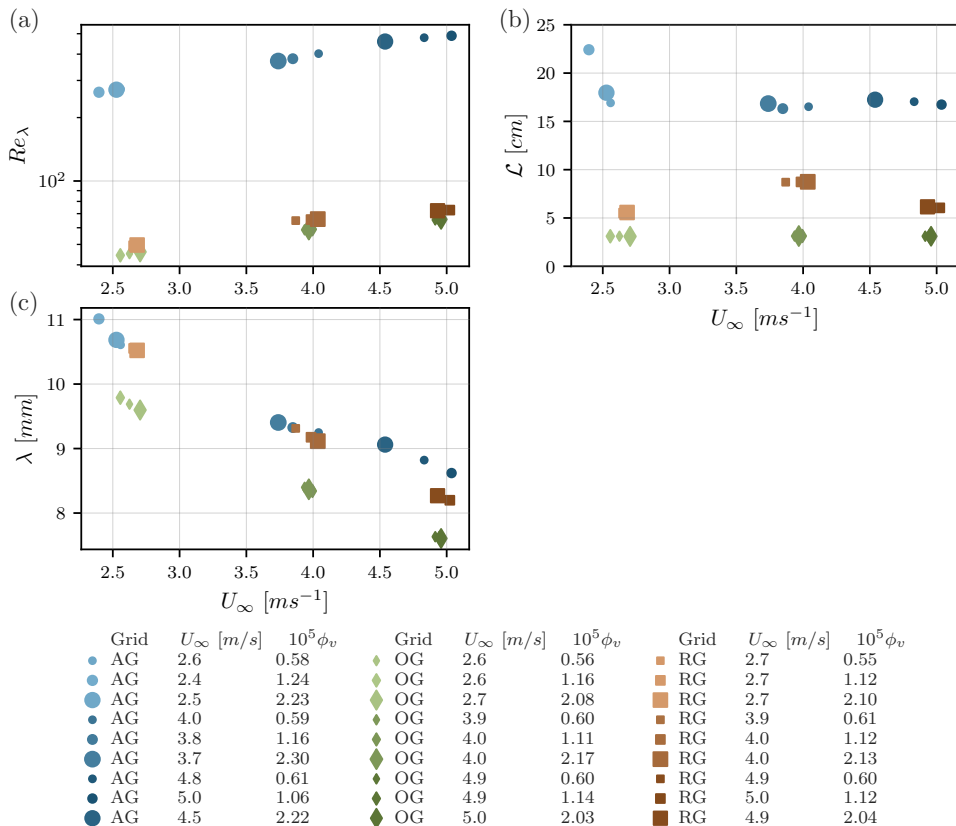


Figure 2: (a) Taylor Reynolds number Re_λ , (b) integral length scale from the integration of the autocorrelation to the first zero-crossing, (c) Taylor microscale λ . All plotted versus the mean streamwise velocity obtained from hot-wire measurements. The different symbols (■), (●) and (◆) represent the regular, active and open grid respectively. The size of the symbol is proportional to the volume fraction and darker colours correspond to higher mean velocities.

310 the particle's vertical velocity and diameter simultaneously. The second beam
 311 is oriented to measure the horizontal velocity. The PDPA measurements were
 312 non-coincident, i.e. horizontal and vertical velocities were taken independently,
 313 since recording only coincident data points can significantly reduce the validation
 314 rate. The particle's horizontal velocity $\langle U \rangle$ is assumed to be very close to the
 315 unladen incoming velocity $\langle U \rangle \approx U_\infty$. Contrary to the study of Mora *et al.*
 316 (2021) in the same facility, the transmitter and the receiver had a smaller
 317 focal length of 500 mm. This enable us to measure the particle vertical velocity
 318 with better resolution. The vertical and streamwise velocity components were
 319 recorded with a resolution of 1 mm/s. The PDPA configuration allow us to
 320 detect particles with diameters ranging from 1.5 μm to 150 μm . We verified that
 321 all velocity distribution were Gaussian, as expected under HIT conditions (see
 322 appendix B). The measurement volume was positioned 3 m downstream of the
 323 droplet injection (at approximately the same streamwise distance as the hot-
 324 wire and Cobra measurements). In order to quantify the effect of recirculation
 325 currents, data were collected on the centreline of the wind tunnel and at a off-
 326 centre location, 10 cm from the wind tunnel wall. For each set of experimental

327 conditions, at least 5×10^5 samples were collected. Depending on the water flow
 328 rate and the wind tunnel inlet velocity, the measurement sampling rate varied
 329 from 20 Hz to 4800 Hz with an average of 1030 Hz and 580 Hz for the streamwise
 330 and vertical velocities, respectively.

331

2.3. Angle correction

333 As the settling velocity is only a small fraction of the the particle velocity, any
 334 slight misalignment of the PDPA with the vertical axis (y) would result in a
 335 large error on the measurements of this important variable. To correct the optical
 336 alignment bias, the misalignment angle β was computed from very small ($d_p <$
 337 $4 \mu\text{m}$) olive oil droplets measurements, as described in Mora *et al.* (2021). Olive
 338 oil generators produce a monodisperse droplet distribution ($\langle d_p \rangle \approx 3 \mu\text{m}$), that
 339 behave as tracers. Using the empirical formula from Schiller & Nauman (Clift
 340 *et al.* (1978)) for the settling velocity of particles, and assuming that the mean
 341 centreline velocity is purely streamwise, the misalignment between the PDPA
 342 and gravity was estimated. Data from the alignment bias correction is given in
 343 appendix C. The angle β was determined to be $\beta = 1.5^\circ \pm 0.3^\circ$. The vertical
 344 velocity measurements were then corrected subtracting the V_β misalignment bias
 345 (proportional to the streamwise velocity and the sine of the misalignment angle).

346 3. Results

347 3.1. Settling velocity of inertial particles as a function of size.

348 Figure 3 presents the corrected averaged settling velocity $\langle V \rangle_D - V_\beta$ against the
 349 diameter D and the Stokes number St . Vertical velocity is defined as positive
 350 when downwards. In all figures, we averaged the settling velocity in 10 μm bins,
 351 from 0 to 150 μm .

352 For each experimental conditions, as expected, the velocity measurements show
 353 that, on average, larger particles have higher settling velocity.

354 3.2. Non-zero mean vertical flow in the limit of very small diameter

355 The ensemble average of the particle equation of motion projected in the direction
 356 of gravity gives:

$$357 \langle v_y^p(t) \rangle = \langle u_y(\mathbf{x}^p(t), t) \rangle + V_T \quad (3.1)$$

358 where y is the vertical coordinate directed towards gravity, $\mathbf{x}^p(t)$ and $v_y^p(t)$ are the
 359 particle position and particle vertical velocity. $u_y(\mathbf{x}^p(t), t)$ is defined as the fluid
 360 vertical velocity at the position of the particle, and V_T is the terminal velocity in
 361 a still fluid.

362 If particles have inertia, they preferentially sample the underlying flowfield
 363 following the preferential sweeping mechanism as described by Maxey (1987),
 364 as a consequence $\langle u_y(\mathbf{x}^p(t), t) \rangle$ differs from the Eulerian mean fluid velocity
 365 $\langle U_y(t) \rangle$. In the absence of particle inertia, they sample uniformly the flowfield
 366 and $\langle u_y(\mathbf{x}^p(t), t) \rangle = \langle U_y(t) \rangle$.

367 Similarly as in Maxey (1987), the one-point Eulerian statistics and the one point
 368 Lagrangian statistics are equal for homogeneous and stationary turbulence. If we
 369 rewrite equation 3.1 for the case of inertialess particles, we get:

$$370 \langle V_y(t) \rangle|_{St=0} = \langle U_y(t) \rangle + V_T|_{St=0} \quad (3.2)$$

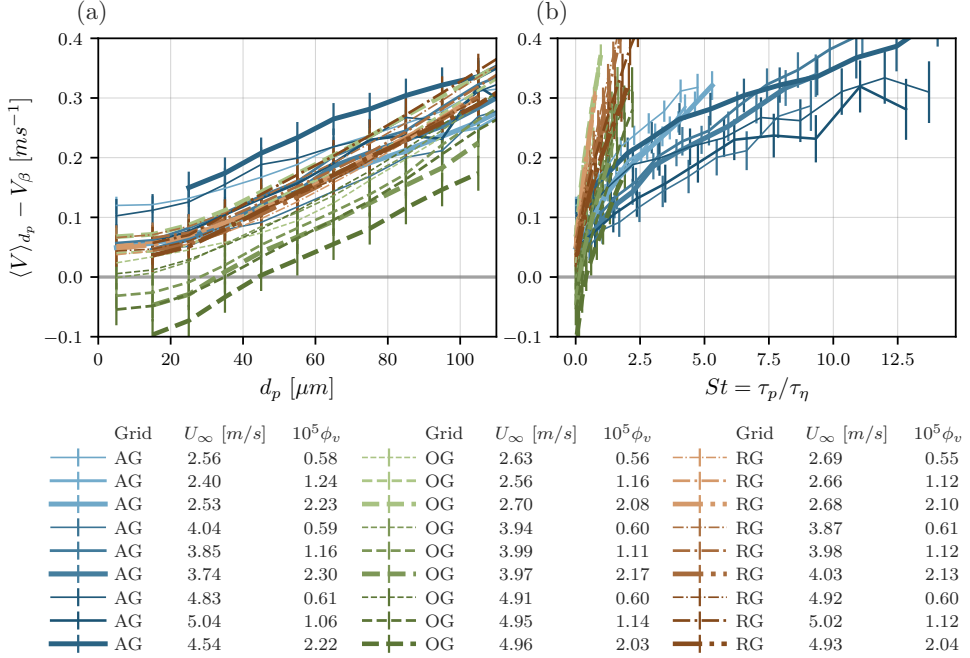


Figure 3: Corrected particle vertical velocity $\langle V \rangle_D - V_\beta$ averaged over bins of $10 \mu\text{m}$ against the diameter (a) and the Stokes number (b). The data from the active grid (AG) are in solid lines, the open grid (OG) in dashed line and the regular grid (RG) in dash-dotted line. The error bars show the estimation of the error in the velocity measurements. Darker colours correspond to higher mean velocities U_∞ and the line width is proportional to the volume fraction.

371 where $\langle V_y(t) \rangle$ is the mean Eulerian particle vertical velocity and $\langle U_y(t) \rangle$ is the
 372 Eulerian mean fluid vertical velocity.

373 In the limit of zero particle inertia, the particle relaxation time τ_p tends to
 374 zero, and therefore V_T (which can be computed as $V_T = g\tau_p$) also tends to zero.
 375 Consequently, in the zero-inertia limit and for very dilute conditions, particles
 376 should behave as tracers and follow the fluid streamlines. Assuming that the
 377 air flow has no mean motion in the vertical direction in the centreline, the
 378 mean corrected vertical particle velocity $\langle V \rangle_D - V_\beta$ should tend to zero for small
 379 diameters.

380 However, experimental data shown in Figure 3 present an offset velocity when
 381 the diameter tends to zero. This offset velocity for very small particle was already
 382 encountered in this facility (Sumbekova (2016); Mora *et al.* (2021)) and suggests
 383 a vertical component due to secondary motion in the air in the wind tunnel,
 384 $\langle U_y(t) \rangle \neq 0$. A mean gas velocity in the vertical direction could be due to two
 385 different physical phenomena. First, as discussed previously, confinement effects
 386 (that would be different for each type of grid) can be responsible for secondary
 387 recirculation motion inside the tunnel. Second, the injection of droplets could
 388 modify the background flow, since falling droplets may entrain gas in their fall.
 389 Even if the volume fraction is low enough for the particles to not affect the global
 390 turbulence statistics, the dispersed phase can exert a significant back reaction
 391 on the fluid in their vicinity (two way coupling effect) (Monchaux & Dejoan

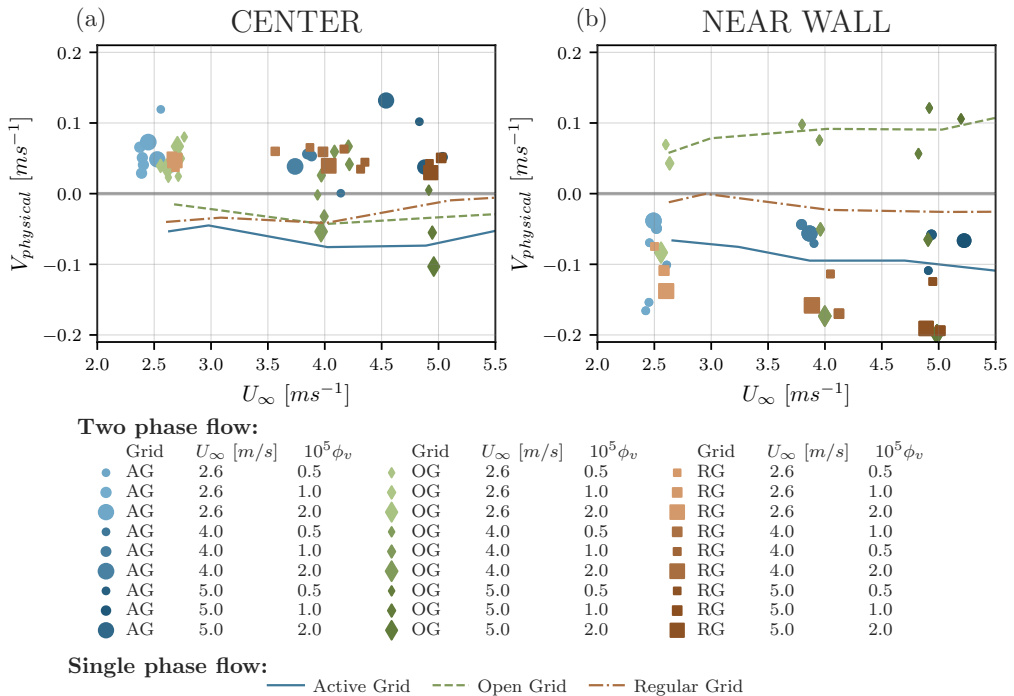


Figure 4: Average settling velocity of the particles for the smallest diameter class, (a) at the centre, and (b) near the wall of the wind tunnel. The different symbols represent the regular (■), active (●) and open grid (◆). The size of the symbols is proportional to the volume fraction and a darker colour correspond to a higher mean velocity. Carrier-phase vertical velocity measurements with the Cobra probe are presented at the two locations with coloured lines. Similar to Figure 3, active grid (AG), open grid (OG) and regular grid (RG) are in solid line, dashed line and dash-dotted line respectively.

392 (2017); Tom *et al.* (2022)). Entrainment in the wake of falling particles might
 393 induced a downward mean gas flow, with a velocity that should be proportional to
 394 the dispersed-phase volume fraction (Alipchenkov & Zaichik (2009); Sumbekova
 395 (2016)). To compensate the downward gas secondary motion near the centreline
 396 of the wind tunnel, an upwards flow in the gas near the walls should be present
 397 (and viceversa for upwards gas velocity at the centreline).

398 Other studies have encountered similar difficulties due to recirculating sec-
 399 ondary motions when measuring particle settling velocity (Wang *et al.* (2018);
 400 Akutina *et al.* (2020)). Akutina *et al.* (2020) corrected for this bias by subtract-
 401 ing the local mean fluid velocity measurements from the instantaneous vertical
 402 velocity of the particle (available in the point-particle simulations).

403 We estimated the existence and strength of recirculating secondary motion
 404 in the wind tunnel by taking PDPa measurements in the centre and close to
 405 the wall of the wind tunnel. We quantified the carrier-phase vertical velocity
 406 using the mean settling velocity of the smallest particles with enough statistical
 407 convergence. This parameter is referred to as $V_{physical}$. Figure 4 shows $V_{physical}$,
 408 measured in the centre (left panel) and near the wind tunnel wall (right panel).

409 Figure 4 shows downward motion ($V_{physical} > 0$) at the centre and upward
 410 motion ($V_{physical} < 0$) near the wind tunnel sidewall, in most cases. A different

behaviour is observed for the open grid (star symbols), with opposite direction of secondary motion, for some volume fractions.

Two possible causes of a mean vertical flow were explained above: confinement effects and the fluid dragging effect of the particles. With Cobra probe measurements, we observed that, even in the absence of particles, recirculating currents arise in the carrier phase. Regarding the fluid dragging effect, there are evidences of the particle back-reaction on the fluid in our measurements since larger values of $V_{physical}$ are observed in the presence of particles than in the measurements without particles. One would expect that the fluid-dragging contribution to $V_{physical}$ would increase with volume fraction (Alipchenkov & Zaichik (2009); Sumbekova (2016)), however there is no clear trend observed for $V_{physical}$ with volume fraction. This lack of volume fraction influence on $V_{physical}$ can be explained by the limited range investigated. In short, the first order contribution to $V_{physical}$ seems to be caused by confinement effects where as a second minor contribution is due to the fluid dragging effect of the particles.

It is worth noticing that the Stokes number could have an influence on $V_{physical}$ as the entrainment of the carrier flow by the dispersed phase is connected to the particle inertia. We would then expect $V_{physical}$ to increase with the average Stokes number of the particles in the flow. In the present experiments, however, the particle size distribution is fixed due to the atomization system. The value of $V_{physical}$, which is the best estimation of the vertical velocity of the carrier flow, results from the interaction of the entire range of diameters (i.e. $St \in [0, 14]$) with the turbulent gas flow. Thus, $V_{physical}$ cannot be computed independently for different particle Stokes numbers. It would then be expected that, in an experiment with different polydispersity, the value of $V_{physical}$ would change because of the different Stokes numbers. While our current experimental setup does not allow for polydispersity variations, further studies may help to understand the role of St in $V_{physical}$.

We also observed recirculating secondary motions in the single-phase flow measured with the Cobra probe. Lines in Figure 4 show the mean single-phase vertical velocity for the three turbulence conditions, against the mean streamwise velocity. Measurements with the Cobra probe provide evidence that there are weak secondary flows in the wind tunnel, even in the absence of particles. Moreover, these secondary flows are dependent on the turbulence generation mechanism, as the open grid (dashed line) causes an opposite sense of motion than the active or regular grids. Surprisingly, single-phase measurements confirm the same trends as the particle velocity measurements. At the most dilute case (i.e. for the lowest volume fraction, the vertical velocity of the secondary motion is the same order of magnitude in the single- and two-phase flows: 0.1 m/s).

In Figure 4, each point corresponds to a single realisation of the experiment, where some realisations are repetitions of the same experimental conditions. We observe low but not insignificant dispersion between the different realisations of the single condition. However, the trend that we discuss is still robust: the sign of $V_{physical}$ does not change for the different realisations of the same conditions, although the magnitude does change.

To conclude, measurements in both laden and unladen flows show the existence of downward motion in the centre and upward motion near the sidewalls (with the active and regular grids, with the opposite sense of motion for the open grid). To the best of the authors' knowledge, this constitutes the first experimental evidence on the existence of $V_{physical}$ as a quantification of the carrier-phase vertical velocity

461 in wind tunnel experiments. From now on, $V_{physical}$ and V_β are subtracted from
 462 the measurements of vertical velocity, $\langle V \rangle_{d_p} - V_\beta - V_{physical}$, to quantify settling
 463 velocity enhancement and/or hindering (corrected from these two experimental
 464 biases).

465 3.3. Influence of the carrier flow turbulent Reynolds number on the particle 466 settling velocity

467 To quantify modifications of the settling velocity, we subtract the particle ter-
 468 minal speed in a stagnant fluid V_T from the vertical velocity. We define this
 469 difference as ΔV , where positive values imply settling velocity enhancement and
 470 negative correspond to hindering. The value of V_T is estimated using the Schiller
 471 & Naumann empirical formula for the particle relaxation time τ_p (Clift *et al.*
 472 (1978)),

$$473 \quad V_T = \tau_p g \quad \text{with} \quad \tau_p = \frac{\rho_p d_p^2}{18\mu_f(1 + 0.15Re_p^{0.687})}, \quad (3.3)$$

474 where μ_f is the carrier flow dynamic viscosity, g the gravitational acceleration, d_p
 475 the particle diameter, $\rho_p = 900 \text{ kg.m}^{-3}$ the oil droplet density and $Re_p = V_T d_p / \nu$
 476 the particle Reynolds number.

477 ΔV is usually normalized by the rms of the carrier-phase fluctuations, u' , or by
 478 the particle terminal velocity, V_T . Normalising ΔV by u' was first proposed by
 479 Wang & Maxey (1993), and Yang & Lei (1998) confirmed u' is a better velocity
 480 scale than u_η to express the settling velocity enhancement. It has been widely
 481 used in other studies (Rosa *et al.* (2016); Huck *et al.* (2018)). Consequently, ΔV
 482 is normalized by u' , although this non-dimensionalisation of ΔV is still under
 483 scrutiny.

484 Figure 5 shows the normalised velocity difference $\Delta V/u'$ against particle diame-
 485 ter. All the measurements were taken at the same location, at the centreline of the
 486 wind tunnel. All the curves show the same trend: the settling velocity is enhanced
 487 for small particles, and this enhancement reaches a maximum, $\max(\Delta V/u')$. After
 488 the maximum, the settling velocity enhancement decreases until it reaches a point
 489 where it is negative, that is, particle settling is hindered by turbulence. For very
 490 large particles (not attainable with our injection system), $\Delta V/u'$ would eventually
 491 become zero as they follow ballistic trajectories, unimpeded by turbulence. A
 492 discussion on the mechanisms that control enhancement and hindering of the
 493 settling velocity is available in section 5.

494 Particle settling velocity tends to depend on the turbulence characteristics,
 495 that is, in this study, it depends on the type of grid used in the experiments.
 496 Series taken with the open-grid configuration show a higher enhancement for all
 497 volume fractions (green dashed line). On the contrary, active-grid turbulence (in
 498 blue solid lines) causes mostly hindered settling, with enhancement present only
 499 for a small range of diameters. Finally, measurements taken with the regular grid
 500 (red dash-dotted lines) show an intermediate behaviour between the two other
 501 grid configurations.

502
 503 A combination between the Rouse and Stokes numbers, $RoSt$, has already
 504 been proven to be an interesting scaling (Ghosh *et al.* (2005)), as it was shown
 505 in several studies to collapse the data better (Good *et al.* (2014); Petersen *et al.*
 506 (2019); Mora *et al.* (2021); Yang & Shy (2021)). The Rouse-Stokes number can

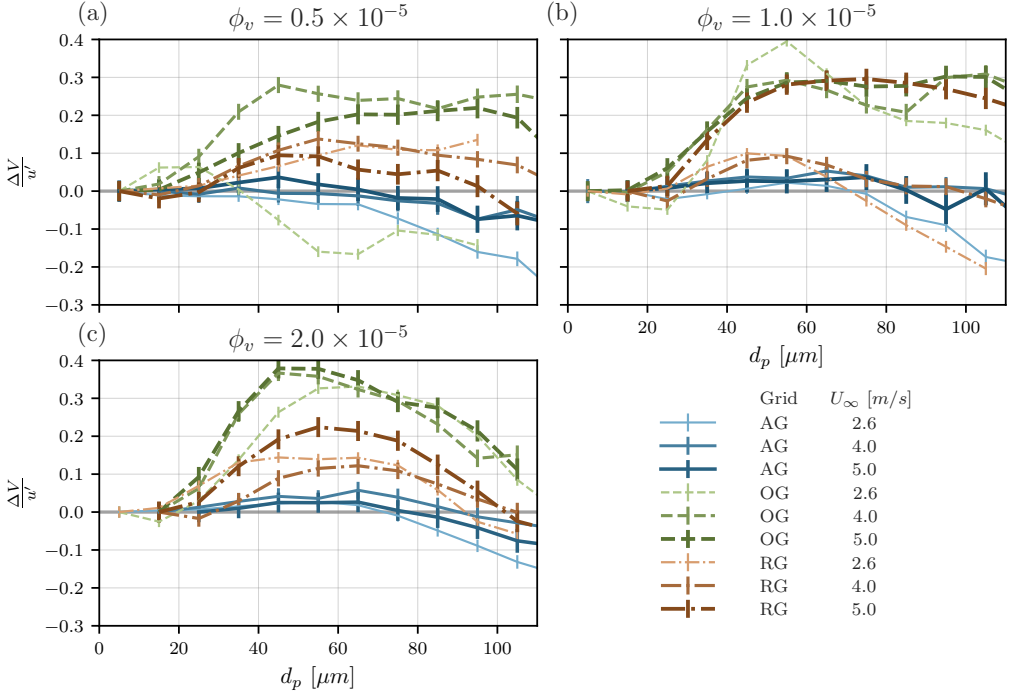


Figure 5: Particle velocity over the carrier phase fluctuations $\Delta V/u' = (\langle V \rangle_{d_p} - V_\beta - V_{physical} - V_T)/u'$ against the particles diameter d_p for a volume fraction of 0.5×10^{-5} (a), 1.0×10^{-5} (b) and 2.0×10^{-5} (c). The data from the active grid (AG) are in solid lines, the open grid (OG) in dashed line and the regular grid (RG) in dash-dotted lines. The errorbars show the estimation of the error in the velocity measurements induced by the determination of the misalignment angle. A darker color correspond to a higher mean velocity U_∞ .

507 be expressed as a ratio between a characteristic length of the particle L_p and a
 508 characteristic length of the flow. L_p can be seen as the distance that a particle
 509 will travel to adjust its velocity to the surrounding fluid starting with a velocity
 510 V_T . Using the Kolmogorov time scale in the Stokes number and u' in the Rouse
 511 number, the Taylor microscale appears to be the characteristic length scale of the
 512 flow:

$$513 \quad RoSt = \frac{\tau_p}{\tau_\eta} \frac{V_T}{u'} = \sqrt{15} \frac{V_T \tau_p}{\lambda} = \sqrt{15} \frac{L_p}{\lambda} \quad \text{with} \quad L_p = V_T \tau_p \quad \text{as} \quad \lambda = \sqrt{15} \tau_\eta u' \quad (3.4)$$

514 In Figure 6, we present $\Delta V/u'$ against the Rouse-Stokes number $RoSt$. Similar
 515 to Figure 5, each panel presents data from a different value of volume fraction.

516 The $RoSt$ number gives a better collapse of the position of maximum of
 517 enhancement than the Rouse number or Stokes number alone. Figure 6 indicates
 518 that enhancement of the settling velocity reaches a maximum for a Rouse-Stokes
 519 number around 0.6, which is consistent with previous findings. Yang & Shy (2021)
 520 reported a maximum for a $RoSt$ around 0.72-1 in a Taylor Couette flow, whereas
 521 Petersen *et al.* (2019) presented a maximum of enhancement for $RoSt$ of order
 522 0.1. Alternative scalings have been tested on our data, with the results provided
 523 for completion in appendix A. These measurements reveal that, for a fixed Re_λ ,

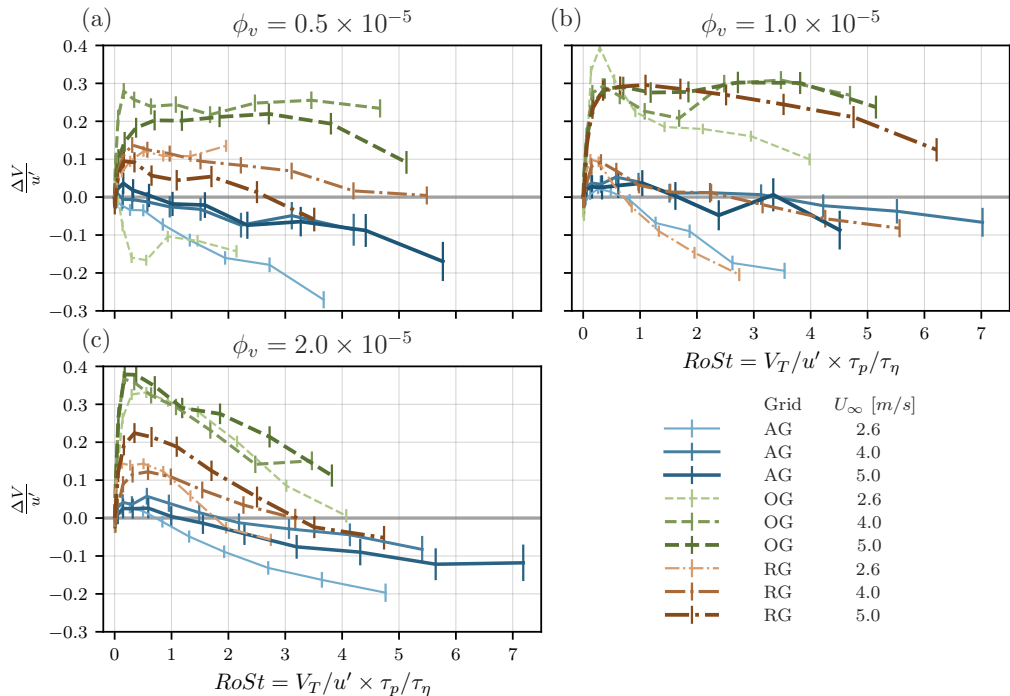


Figure 6: Enhancement of the particle velocity, normalised by the turbulent rms velocity, $\Delta V/u'$, against the Rouse-Stokes number. (a) $\phi = 0.5 \times 10^{-5}$, (b) $\phi = 1.0 \times 10^{-5}$ and (c) $\phi = 2.0 \times 10^{-5}$. Lines follow the legend of Figure 5.

524 the enhancement increases with volume fraction, consistent with Aliseda *et al.*
 525 (2002) and Monchaux & Dejoan (2017).

526 We observe that the enhancement is much stronger for the low values of Re_λ
 527 ($\in [30-70]$, open and regular grids) than for the higher Re_λ ($\in [260-520]$, active
 528 grid) for all volume fractions. As shown in Figure 2(a), the settling enhancement
 529 decreases significantly with an increase in the flow Taylor Reynolds number, with
 530 Taylor Reynolds number significantly higher for the active grid turbulence than
 531 for the two other grids $Re_{\lambda AG} \gg Re_{\lambda RG} > Re_{\lambda OG}$. However, we observe when
 532 the Taylor Reynolds number is varied by increasing the inlet velocity U_∞ alone,
 533 while keeping the same grid turbulence generation system, the trend is reversed:
 534 the settling enhancement increases with an increase in Re_λ within the small
 535 range achieved with each grid, and keeping a quasi-constant large-to-small scales
 536 ratio. Thus, settling enhancement depends strongly on the characteristics of the
 537 turbulence, as reported in Mora *et al.* (2021). While the study of Mora *et al.*
 538 (2021) obtained the same trend by comparing against data from the literature, in
 539 this study the entire range of Reynolds number and turbulent length scales were
 540 explored in the same facility.

541 This would suggest that the maximum of enhancement has a non-monotonic behav-
 542 iour with the turbulent Reynolds number, as reported in (Mora *et al.* (2021)).
 543 A non-monotonic dependency of the degree of enhancement with Reynolds number
 544 has also been observed recently in Yang & Shy (2021). This effect of Re_λ on
 545 the maximum of enhancement confirms that the settling velocity modification is

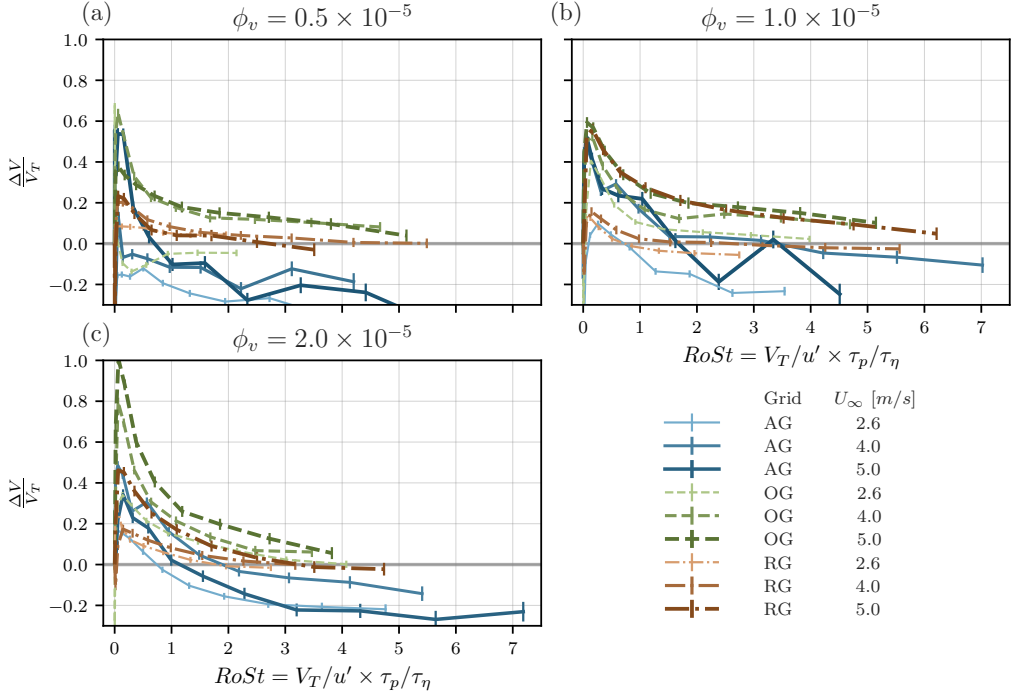


Figure 7: Enhancement of the particle velocity, normalised by the particle terminal velocity, $\Delta V/V_T$, against the Rouse-Stokes number. (a) $\phi = 0.5 \times 10^{-5}$, (b) $\phi = 1.0 \times 10^{-5}$ and (c) $\phi = 2.0 \times 10^{-5}$. Lines follow the legend of Figure 5.

546 a multiscale phenomenon and one turbulent scale is not sufficient to characterise
 547 it (Tom & Bragg (2019)).

548 Although u' has been widely used in the literature to normalise ΔV , it has
 549 already been pointed out that there is no consensus on the scale for settling
 550 modification (Tom & Bragg (2019)). The influence of the Reynolds number on
 551 the settling modification is also affected by normalising ΔV with u' . Since the
 552 range of flow scales that interact with the particles depends on the Stokes number,
 553 an interesting choice would be to non-dimensionalise ΔV with a vertical velocity
 554 that depend on St . Similarly to previous studies (Good *et al.* (2014); Rosa *et al.*
 555 (2016)), a normalisation of the results with the terminal velocity $V_T = Stg\tau_\eta$
 556 is proposed in Figure 7. Figure 7 uses the same legend as Figures 5 and 6.
 557 Normalising with V_T , the three different sets of curves for the three turbulence
 558 generation schemes are observed to collapse in Figure 6. However, looking closely
 559 at Figure 7, the Reynolds number dependency of the settling velocity modification
 560 is still non-monotonic, even after normalising with a velocity scale different than
 561 u' .

562

3.4. Variance of the vertical particle velocity

563 The variance of the vertical particle velocity $\langle (v'_y)^2 \rangle$ normalised by the Kol-
 564 mogorov velocity square is shown in Figure 8. In Figure 8(a), we observe that
 565 the variance increases with the Reynolds number Re_λ . This is expected since the
 566 fluid velocity variance increases with the Reynolds number so the particle velocity
 567 variance. The normalised particle velocity variance was also computed for each

bin of diameters to have the influence of the Stokes number and the Rouse number on this metric. Panel Figure 8(b) shows that the variance decreases slowly with the Rouse-Stokes number. This is consistent with the fact that the filtering by inertial particles becomes more important as inertia increases. Inertial particles with higher Stokes number are less sensitive to the carrier flow's high velocity fluctuations.

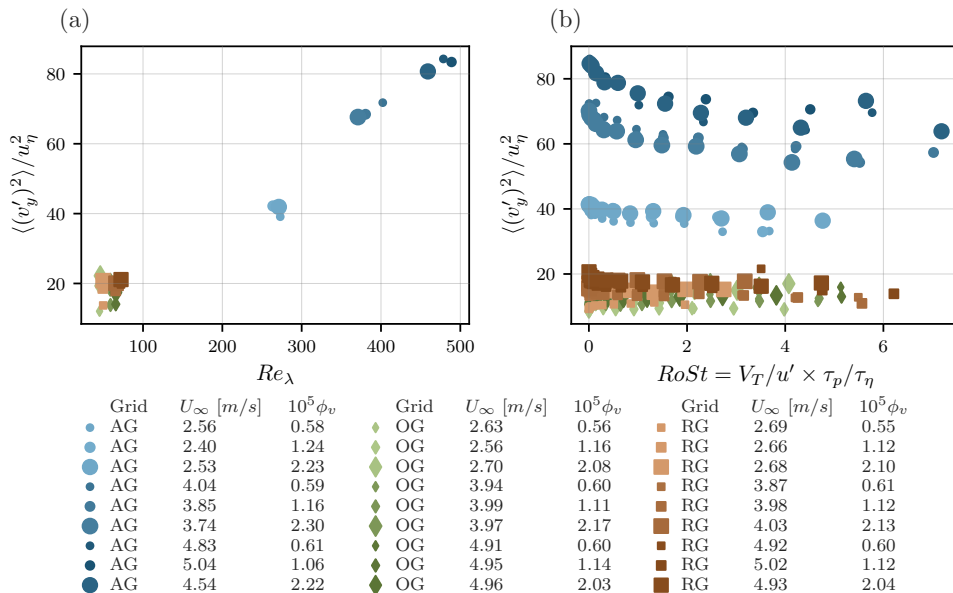


Figure 8: Variance of the vertical particle velocity $\langle (v'_y)^2 \rangle$ normalised by the Kolmogorov velocity square u_η^2 . The variance is plotted towards the Reynolds number Re_λ in the left panel (a) and towards the Stokes number in the right panel (c). The symbols follow the legend of Figure 4.

574

3.5. Scaling of the maximum of enhancement

As no theoretical consensus have been found on the settling velocity modification, empirical scalings are proposed. This study focuses on the value and location of maximum of enhancement $\max(\Delta V/u')$, and not on the critical $RoSt$, where enhancement turns into hindering, as most cases with the passive grid did not reach the transition enhancement/hindering for high Rouse number, contrary to Mora *et al.* (2021). As said in the previous section, the enhancement seems to increase when varying only the wind tunnel velocity U_∞ . In order to take this trend into account, a global Reynolds number is introduced $Re_G = MU_\infty/\nu$ base on U_∞ and M the mesh spacing in the turbulence-generating grid. Several dimensionless parameters were tested to scale $\max(\Delta V/u')$: the global Reynolds number Re_G , the volume fraction ϕ_v , the Taylor-scale Reynolds number Re_λ , a Reynolds number based on the integral length scale, and the Ro or St numbers corresponding to the maximum of enhancement. The best scaling from the parameters above was found to be a combination of Re_λ , Re_G and ϕ_v .

Figure 9(a) represents $\max(\Delta V/u')$ against $Re_\lambda^\alpha \phi_v^\beta Re_G^\gamma$, where α , β and γ are

589

590 best-fit exponents:

$$591 \quad \max(\Delta V/u') \sim Re_\lambda^\alpha \phi_v^\beta Re_G^\gamma \quad (3.5)$$

592 with $\alpha = -1.1$, $\beta = 0.6$ and $\gamma = 0.9$. The values of α , β and γ are consistent with
 593 previous observations: the maximum of enhancement increases with inlet velocity
 594 and volume fraction but decreases with an overall increase of Re_λ (when varying
 595 the Reynolds number on the entire range [30, 520]).

596 Figure 9 show the third panel of Figure 6 with $\Delta V/u'$ divided by the power
 597 law scaling. A gap in data exists due to the jump in Reynolds number between
 598 the active grid and the two passive grids (see Figure 2). No measurements were
 599 taken for Re_λ between 70 and 260, since the present experimental setup cannot
 600 reach those intermediate values.

601 Figure 9 shows that no simple scaling of the peak of settling enhancement can
 602 be inferred from this data. The dispersion of the results is partly due to the effect
 603 of the different large scale turbulence, as discussed in the next section.

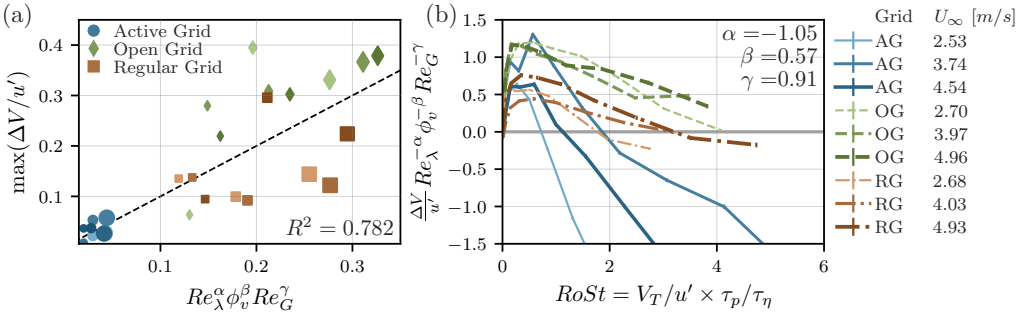


Figure 9: Scaling of the settling velocity with Re_λ , Re_G and ϕ_v . (a) $\max(\Delta V/u')$ versus $Re_\lambda^\alpha \phi_v^\beta Re_G^\gamma$ with the fitted value of α , β and γ . (b) $\max(\Delta V/u')$ divided by the scaling versus the Rouse Stokes number.

604 4. Influence of large-scale structures

605 Although the open and regular grids create very similar values of turbulent
 606 intensity, the settling speed of inertial particles in these two flows are very
 607 different. Indeed, regular grid data (dash-dotted lines) is as different from open
 608 grid data as it is from active grid data (see Figures 5 and 6). This discrepancy
 609 between regular and open-grid behaviours can be explained by the difference in
 610 integral length scales between these two turbulent flows (see table 1 and Figure
 611 2).

612 Figure 10 illustrates the settling velocity modification from two series with
 613 similar Reynolds numbers, turbulent intensities and volume fractions, but differ-
 614 ent integral length scales \mathcal{L} . The figure is plotted against $RoSt$ but presents a
 615 similar trend when made with Ro or St . It can be seen that the degree of settling
 616 enhancement is stronger for a smaller integral length scale and this behaviour
 617 is consistent for different volume fractions and wind tunnel Reynolds numbers.
 618 This suggests that the integral length scale and large-scale structures play a
 619 role in the settling velocity modification. According to the study of Tom &
 620 Bragg (2019), there is a length scale $l_c(St)$ above which the effects of particle
 621 inertia are negligible and only the flow scales smaller than l_c contribute to the

622 settling velocity enhancement. l_c has been proposed to be an increasing function
 623 of the Stokes number, thus, as St increases, the range of flow scales impacting
 624 the settling velocity becomes larger. Consequently, we would expect the integral
 625 length scale to play a role on $\Delta V/u'$ only when the Stokes number is above
 626 $St(l_c)$. With our experiments, we provide the first evidence of settling velocity
 627 modification by turbulence where the integral length scale is the only difference
 628 between two turbulent datasets, in Figure 10. According to the l_c hypothesis, one
 629 would expect the curves from the regular grid and the open grid to collapse for the
 630 $St < St(l_c)$ data. Figure 10 reveals that the integral length scale has a measurable
 631 influence on the settling velocity modification for almost the entire range of $RoSt$
 632 number studied, and not only for the large $RoSt$. The data presented in Figure 10
 633 shows a collapse for $RoSt < 0.1$, suggesting that the integral length scale does not
 634 play a role in settling velocity modification for very small $RoSt$. This contradicts
 635 the hypothesis in Tom & Bragg (2019), unless $l_c < \mathcal{L}$ for the smallest particles in
 636 the flow and $l_c > \mathcal{L}$ for larger particles. However, Tom & Bragg (2019) showed
 637 that $l_c(St)$ is larger than expected and can be larger than the flow integral scale
 638 even for $St = O(0.1)$.

639 As a consequence of the evidence provided in this paper, the preferential
 640 sweeping mechanism is more accurate at explaining the observations in flows
 641 where the large-scale structures are reduced in size.

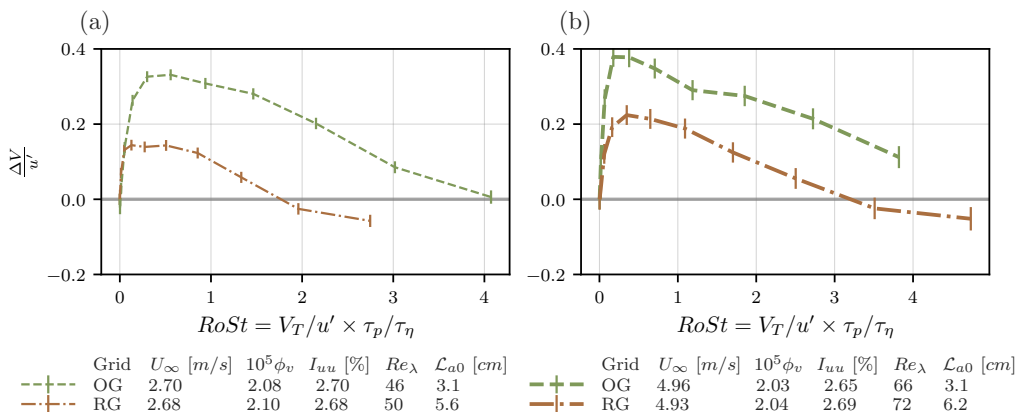


Figure 10: Open and regular grid data. Settling velocity difference over the carrier-phase fluctuations $(\Delta V)/u'$ against the Rouse-Stokes number, for a volume fraction of 2.0×10^{-5} . The left panel displays data taken with an inlet velocity of 2.7 m/s, whereas the bulk velocity in panel (b) is 5.0 m/s.

642 5. Mechanisms of the settling velocity modification

643 5.1. Competition between preferential sweeping and loitering

644 The different models of the settling velocity modification require the measurement
 645 of fluid variables (flow structure, slip velocity, etc.) that is not possible, at
 646 least in an instantaneous manner, in large Reynolds number two-phase flows.
 647 Nevertheless, qualitative comparison of our experimental data with theoretical
 648 models for the proposed mechanisms shows good agreement. The enhancement
 649 of the settling velocity for small Stokes number, i.e. small diameter, particles
 650 found in our experiments is consistent with the preferential sweeping mechanism

651 (Maxey (1987)). The hindering for large Stokes number found at high Reynolds
 652 numbers, on the other hand, is consistent with the loitering mechanism proposed
 653 by Nielsen (1993). The mechanisms and the parameters that control the transition
 654 between enhancement and hindering, for which this manuscript provides novel
 655 data at turbulent Reynolds numbers and length scales not studied before, remain
 656 poorly understood and need theoretical analysis.

657 Indeed, the Ro , St or $RoSt$ critic that set the transition between enhancement
 658 and hindering have a non-monotonic dependence with the Reynolds number.
 659 No simple scaling of the Stokes or Rouse critic could be found from other non
 660 dimensional parameters (i.e. volume fraction, global Reynolds number or Taylor
 661 based Reynolds). However the fact that the maximum of enhancement collapses
 662 for $RoSt \approx 0.6 - 1.0$ gives a threshold for which the loitering effect starts to
 663 balance out the preferential sweeping mechanism (although enhancement remains
 664 the main outcome).

665 As mentioned before, the $RoSt$ number can be expressed as the ratio between
 666 L_p and λ , where L_p is the distance that a particle will travel to adjust its velocity
 667 to the surrounding fluid starting with a velocity V_T . Furthermore, the Taylor
 668 microscale can be seen as the separation between two large-scale eddies (Mazellier
 669 & Vassilicos (2008)). When L_p starts to be larger than λ preferential sweeping
 670 mechanism becomes less and less important since particles take a longer time and
 671 distance to respond to the fluid. As particles are less often swept in the downward
 672 side of eddies with an increase in L_p they cross both upward and downward regions
 673 of the flow which result in a more frequent loitering. Consistently, Figure 10 shows
 674 that the preferential sweeping mechanism is more effective when the flow large
 675 scale structure are smaller.

676

5.2. Collective effects

677 Numerous studies have shown an increase in the particle settling velocity with the
 678 particle local concentration (Aliseda *et al.* (2002); Monchaux & Dejoan (2017);
 679 Huck *et al.* (2018)). An estimate of the particle local concentration can be
 680 obtained with the use of Voronoï tessellations (Monchaux *et al.* (2010)). In this
 681 study, only unidimensional statistics of a three-dimensional flow are collected
 682 with the PDPA. For such signals, special attention is required as the analysis
 683 of preferential concentration via Voronoï tessellations has shown to present some
 684 bias (Mora *et al.* (2019a)). A Voronoï cell is defined as the portion of the temporal
 685 signal closer to one particle than to any other ones. The inverse of the Voronoï
 686 cell length L gives an indication of the particle local concentration $C = 1/L$.
 687 Preferential concentration is observed when small and large Voronoï cells are
 688 over represented compared to a random Poisson process (RPP). In other words,
 689 the probability distribution function (PDF) of the normalised Voronoï cell length
 690 $\mathcal{V} = L/\langle L \rangle$ crosses the PDF of a random Poisson process twice. Before the first
 691 crossing, small Voronoï cell are over represented showing the presence of over
 692 populated regions, clusters. Similarly, after the second crossing large Voronoï cells
 693 are more probable than for a RPP showing the presence of depleted regions (i.e.
 694 voids). Clusters and voids are defined as group of connected cells with cell length
 695 smaller than the first, respectively larger than the second, crossing with the PDF
 696 of a random Poisson process. According to Mora *et al.* (2019a), clustering can
 697 be present and not be detected by the use of 1D Voronoï tessellations. However if
 698 the standard deviation of the normalised cell length σ_ν is larger than for a RPP
 699 distribution $\sigma_\nu > \sigma_{RPP}$, it is a reliable evidence of the presence of preferential

700 concentration. For the next, we will only consider cases for which $\sigma_v/\sigma_{RPP} > 1.2$
 701 to avoid time series that present a lack of information.

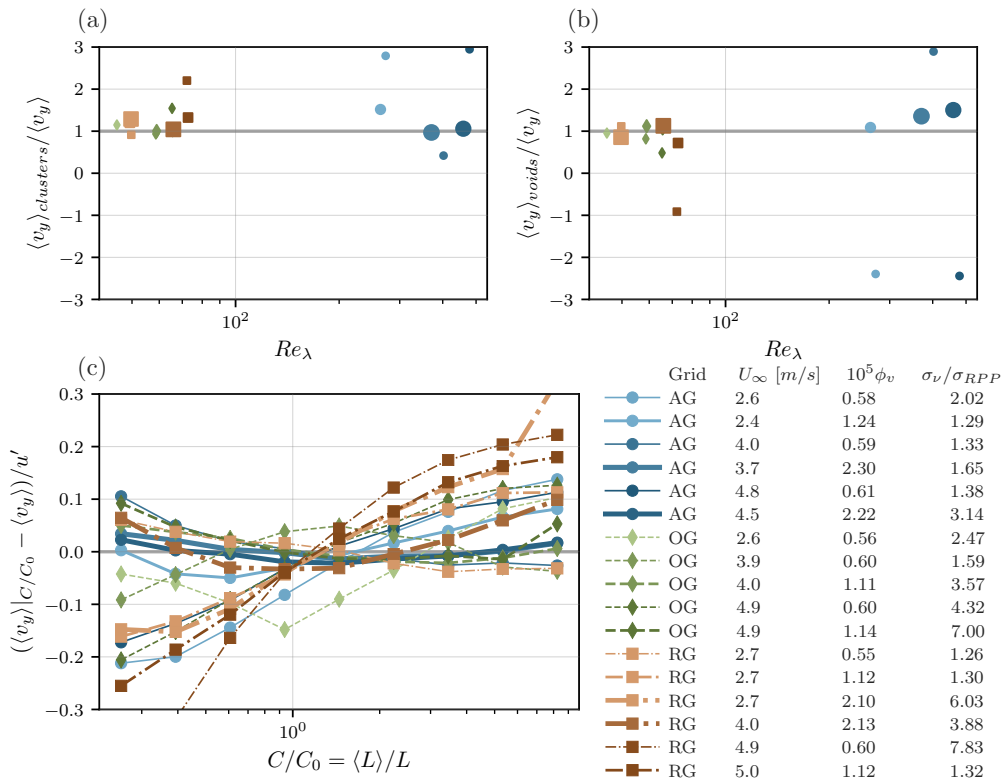


Figure 11: Mean settling velocity of particles in clusters $\langle v_y \rangle_{clusters}$ (a) and particles in voids $\langle v_y \rangle_{voids}$ (b) normalised by the unconditional average $\langle v_y \rangle$.

Panel (c) shows the settling velocity conditioned on the particle local concentration $\langle v_y \rangle|_{C/C_0}$ normalised by the r.m.s. of the carrier phase fluid fluctuations. Symbols and lines follow the legend of Figure 4.

702 Figure 11(c) shows the conditional particle velocity on the local concentration
 703 compared to the average settling velocity over all particles $\langle v_y(t) \rangle$ versus the
 704 normalised concentration $C/C_0 = 1/\mathcal{V}$. In agreement with previous studies (Huck
 705 *et al.* 2018), the settling velocity is constant or increased with the particle local
 706 concentration.

707 The mean settling velocity for particles in clusters and particles in voids are
 708 shown in panels (a) and (b) of Figure 11. For low Reynolds number, the settling
 709 velocity for particles in clusters is, for most cases, larger than the global settling
 710 while particles in voids settle slower than the unconditional average. Figure 11
 711 show that the particle local concentration and collective effects have an influence
 712 on the settling rate in our dataset as previously observed in Aliseda *et al.* (2002);
 713 Huck *et al.* (2018); Petersen *et al.* (2019).

714

5.3. Sweep-stick mechanism

715 The sweep-stick mechanism proposed by (Chen *et al.* 2006; Goto & Vassilicos
 716 2008; Coleman & Vassilicos 2009) states that there is a strong correlation between

717 the carrier flow zero-acceleration points and inertial particle positions. This
 718 mechanism was first proposed to explain the preferential concentration of inertial
 719 particles for direct numerical simulation data with zero gravity. The modified
 720 sweep-stick mechanism (Falkinoff *et al.* 2020) suggests that, in presence of
 721 gravity, particles stick to low, but non-zero, acceleration points. Zero-acceleration
 722 points were shown to have an average lifetime of $\tau_{\mathcal{L}}$ with $\tau_{\mathcal{L}} = \mathcal{L}/u'$ the flow
 723 integral time scale (Coleman & Vassilicos 2009). This mechanism is restricted to
 724 cases where the particle relaxation time is much smaller than the zero acceleration
 725 points life-time, that is to say when $\tau_p \ll \tau_{\mathcal{L}}$ or $St_{\mathcal{L}} = \tau_p/\tau_{\mathcal{L}} \ll 1$ and for $St > 1$.

726 The average acceleration of the fluid at the particle's position can be estimated
 727 from the ensemble average of Maxey Riley equation:

$$728 \quad \frac{\langle v_y^p(t) \rangle}{V_T} = \frac{\langle u_y(\mathbf{x}^p(t), t) \rangle}{V_T} + 1 \quad (5.1)$$

729 Similarly as in Falkinoff *et al.* (2020), we use the approximation that
 730 $\langle a_y(\mathbf{x}^p(t), t) \rangle \sim \langle u_y(\mathbf{x}^p(t), t) \rangle / \tau_{\mathcal{L}}$ with $a_y(\mathbf{x}^p(t), t)$ the fluid acceleration
 731 at the particle position. The term $\langle u_y(\mathbf{x}^p(t), t) \rangle / V_T$ can be rewritten as
 732 $\langle a_y(\mathbf{x}^p(t), t) \rangle / (gSt_{\mathcal{L}})$ with $St_{\mathcal{L}} = \tau_p / \tau_{\mathcal{L}}$.

$$733 \quad \frac{\langle a_y(\mathbf{x}^p(t), t) \rangle}{gSt_{\mathcal{L}}} = \frac{\langle v_y^p(t) \rangle}{V_T} - 1 \quad (5.2)$$

734 Then with the fact $\tau_{\mathcal{L}} = \mathcal{L}/u'$ and $St_{\mathcal{L}}/St = \tau_{\eta}u'/\mathcal{L}$ we get:

$$735 \quad \frac{\langle a_y(\mathbf{x}^p(t), t) \rangle}{gSt} = (\tau_{\eta}u'/\mathcal{L}) \left(\frac{\langle v_y^p(t) \rangle}{V_T} - 1 \right) \quad (5.3)$$

736 To be able to compare with the data from Falkinoff *et al.* (2020) for which
 737 the vertical axis is directed in the opposite direction, we plot the quantity
 738 $(\tau_{\eta}u'/\mathcal{L})(1 - \langle v_y^p(t) \rangle / V_T)$ in Figure 12. This quantity is positive when there is
 739 hindering ($\langle v_y^p(t) \rangle < V_T$) and negative in case of enhancement ($\langle v_y^p(t) \rangle > V_T$).

740 Figure 12 presents the estimation of the normalised fluid acceleration at the
 741 particles' position for the active grid data. The data from the direct numerical
 742 simulation of Falkinoff *et al.* (2020), also shown in Figure 12, correspond to
 743 a turbulent flow Reynolds number of $Re_{\lambda} \approx 300$, various Stokes numbers and
 744 Froude number ($St = 1, 3, 6, 8, 9$), and Froude numbers ($Fr = (\varepsilon^3/\nu)^{1/4}1/g =$
 745 $0.15, 0.23, 0.45, 1.36$). As for the experimental data the fluid velocity at the par-
 746 ticle position is not accessible, we can only compare the value of the acceleration
 747 of the fluid elements between the experiments and the simulation. To better
 748 compare with the numerical simulation, only samples taken with the active grid
 749 and with a St number close to 1, 3, 6, 8, 9 are presented in Figure 12. There is a
 750 reasonable agreement in the value of $\langle a_y(\mathbf{x}^p(t), t) \rangle / (gSt_{\mathcal{L}})$ between both studies.
 751 The slope of the data is controlled by the value of $\tau_{\eta}u'/\mathcal{L}$, thus depends only upon
 752 the flow characteristics. Discrepancies can be found between the values from the
 753 numerical simulation and the experiment since the Froude number and the flow
 754 integral length scale are different.

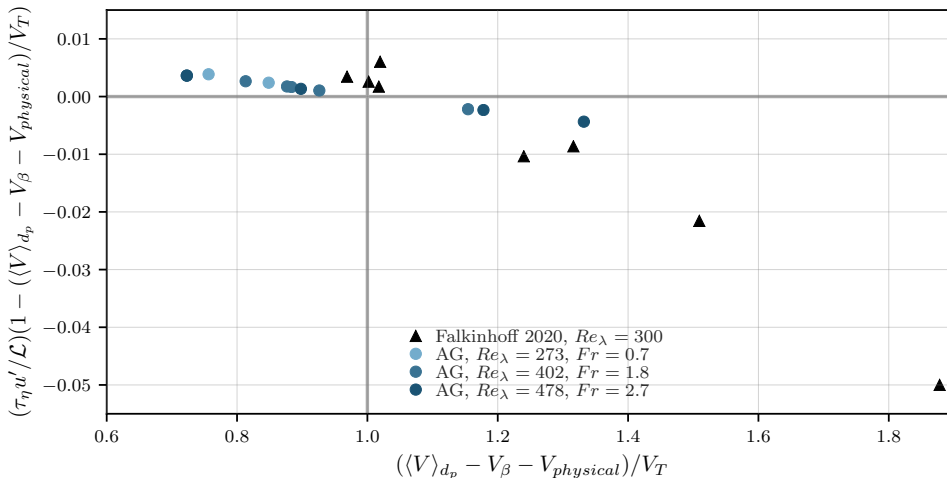


Figure 12: Average normalised acceleration of the fluid elements $\langle a_y(\mathbf{x}^p(t), t) \rangle / (gSt)$ following equation 5.3 as a function of the corrected settling velocity normalised by the terminal velocity $\langle (V)_{d_p} - V_\beta - V_{physical} \rangle / V_T$. The black triangles present the data from the study of Falkinhoff *et al.* (2020). The data from the present study, taken with the active grid and a volume fraction of 0.5×10^{-5} , are shown in blue.

755 6. Conclusion

756 The settling velocity of sub-Kolmogorov inertial particles in wind tunnel decay-
757 ing turbulence is presented and analyzed. Accurate settling velocity measure-
758 ments were carefully collected and calibrated, by correcting different experimental
759 sources of potential bias. First, a correction for PDPA misalignment angle is
760 computed and applied. Second, secondary flows in the wind tunnel test section
761 were characterised, $V_{physical}$, for both single-phase and two-phase flows. High
762 resolution in the vertical velocity, compared to Mora *et al.* (2021), was obtained
763 thanks to a new PDPA setup. This, together with the detailed measurements of
764 alignment and secondary motions, created a more accurate dataset of settling
765 velocity for small Stokes number particles.

766 The results in this study confirm and extend the trends observed previously
767 (among others by Wang & Maxey (1993); Aliseda *et al.* (2002); Good *et al.*
768 (2014); Mora *et al.* (2021)). Specifically, the settling velocity enhancement, that
769 has been observed under a wide range of conditions, disappears with an increase of
770 global (wind tunnel) Reynolds number, and turns to hindering at high Reynolds
771 numbers $Re_\lambda > 260$. This dependence with Reynolds number is in contradiction
772 with most numerical studies (Bec *et al.* (2014); Rosa *et al.* (2016); Tom & Bragg
773 (2019)). However, for a smaller range of Reynolds numbers, the maximum of
774 enhancement is proportional to the inlet velocity U_∞ , and therefore to the global
775 Reynolds number. A new phenomenological scaling considering the influence of
776 the bulk velocity has been proposed.

777 The range of volume fractions investigated is limited, and precludes the in-
778 fluence of this variable on settling enhancement to appear. Different turbulence
779 generation schemes allow for flows with different integral and Taylor length scales,
780 at the same turbulent intensities and Reynolds numbers. We show that even if the

781 Reynolds number and the turbulent intensity are similar, significant differences
 782 in the settling modification remain, due to widely different integral length scales.
 783 This suggests an important role of the large flow structures on the settling velocity
 784 modification.

785 The settling rate modification observed in this study is due to the interven-
 786 tion of several mechanisms, including at least preferential sweeping, loitering
 787 and sweep-stick mechanism, operating on different ranges of Stokes and Rouse
 788 numbers. In addition to the aforementioned mechanisms, our results show that
 789 collective effects might take a part in the settling velocity modification.

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 793 Govart for producing experimental rigs.

794

795 The authors report no conflict of interest.

796 **Appendix A. Additional scalings.**

797 Particle settling velocity is often presented against the Stokes number (Wang
 798 & Maxey (1993); Yang & Lei (1998); Aliseda *et al.* (2002); Good *et al.* (2014);
 799 Rosa *et al.* (2016); Petersen *et al.* (2019); Yang & Shy (2021)), the Rouse number
 800 (Good *et al.* (2012, 2014); Mora *et al.* (2021)) and a Rouse number based on the
 801 Kolmogorov scale V_T/u_η (Good *et al.* (2014)). Figure 13 show the present data
 802 against these three different parameters.

803 **Appendix B. Stationnarity of the temporal signal and PDF of** 804 **particles’ velocities.**

805 In this section we show the raw velocity obtained with the PDPA. The temporal
 806 signals are stationary (see Figure 14). In this figure, one portion of the time
 807 signals is presented for each of the three grids using a volume fraction of $\phi_v =$
 808 1.0×10^{-5} and an inlet velocity of $U_\infty \approx 4.0$ m/s. The left panel corresponds to
 809 the streamwise velocity whereas the right panel represents the vertical velocity.

It can also be observed that all inertial particles horizontal and vertical veloc-
 ities have a Gaussian distribution (see Figure 15). The skewness ($\mu_3/\mu_2^{3/2}$) and
 the kurtosis (μ_4/μ_2^2) have been computed for each velocity distribution, (with μ_n
 the nth central moment). The average values over all these experiments for both
 of these moments are :

$$\frac{\mu_3}{\mu_2^{3/2}}(V_x) = -0.12, \quad \frac{\mu_4}{\mu_2^2}(V_x) = 3.00, \quad \frac{\mu_3}{\mu_2^{3/2}}(V_y) = 0.08 \quad \text{and} \quad \frac{\mu_4}{\mu_2^2}(V_y) = 3.17 .$$

810 In Figure 16 the skewness and the kurtosis for each velocity pdf is shown against
 811 the mean streamwise velocity U_∞ . Since the skewness always falls between -0.5
 812 and 0.5, the velocity distribution are considered symmetrical. The values of the
 813 flatness are also relatively close to 3, the value of the Gaussian distribution.

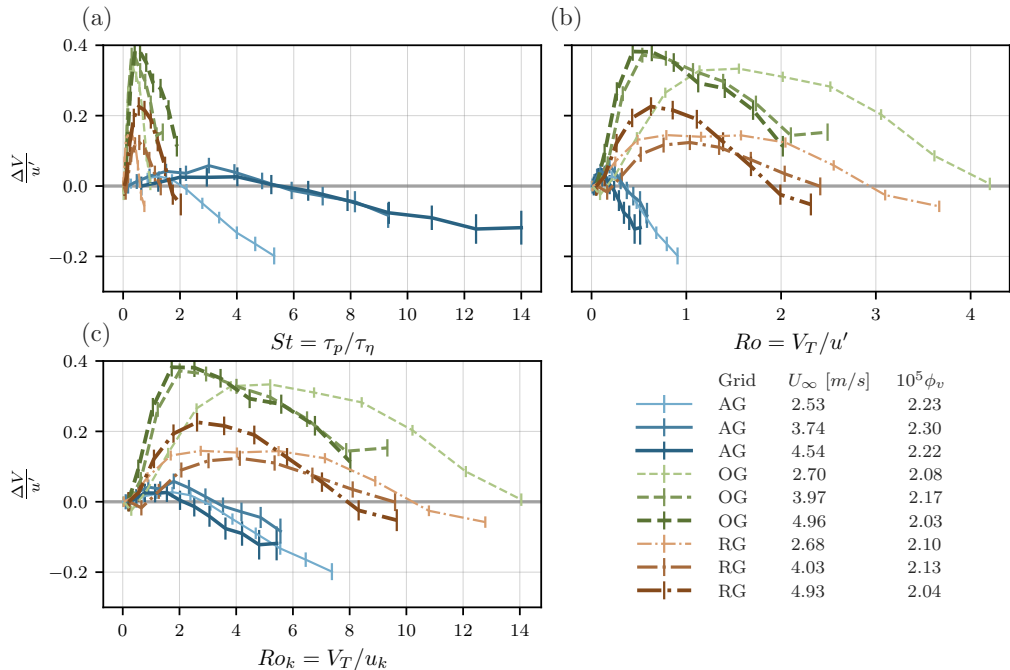


Figure 13: Particle velocity over the carrier phase fluctuations $\Delta V/u'$ against the Stokes number (a), Rouse number (b) and the Rouse number based on the Kolmogorov scale (c) for a volume fraction of 2.0×10^{-5} . Line styles follow the caption of Figure 5.

814 Appendix C. Determination of the PDPA misalignment angle.

815 A small deviation angle between the PDPA axes and the wind tunnel axes is
 816 always present even if the best precautions were taken during the setup of the
 817 device. The deviation angle has a negligible impact on the horizontal velocity but
 818 can induce a significant bias on the measurements of the settling velocity, since
 819 the particle's horizontal velocity component is much larger than the vertical one.

820 We call β the angle between the axes of the PDPA and the axes of the
 821 wind tunnel. V_{XPDA} and V_{YPDA} are respectively the streamwise and vertical
 822 components of the velocity measured by the instrument while V_{XWT} and V_{YWT}
 823 are the exact particle velocity component in the wind tunnel coordinate system
 824 (see Mora *et al.* (2021)).

825 By projecting the accurate droplet velocity in the frame of reference of the
 826 PDPA we get:

$$827 \quad \overrightarrow{V_{YWT}} = \left(\underbrace{V_{YPDA} \cos(\beta)}_{\approx V_{YPDA}} - V_{XPDA} \sin(\beta) \right) \vec{y} \quad (C1)$$

828 Since the PDPA was set in noncoincident mode, we do not have access to
 829 the horizontal component V_{XPDA} corresponding to the biased settling velocity.
 830 We then approximate by using the mean of the time series horizontal velocity

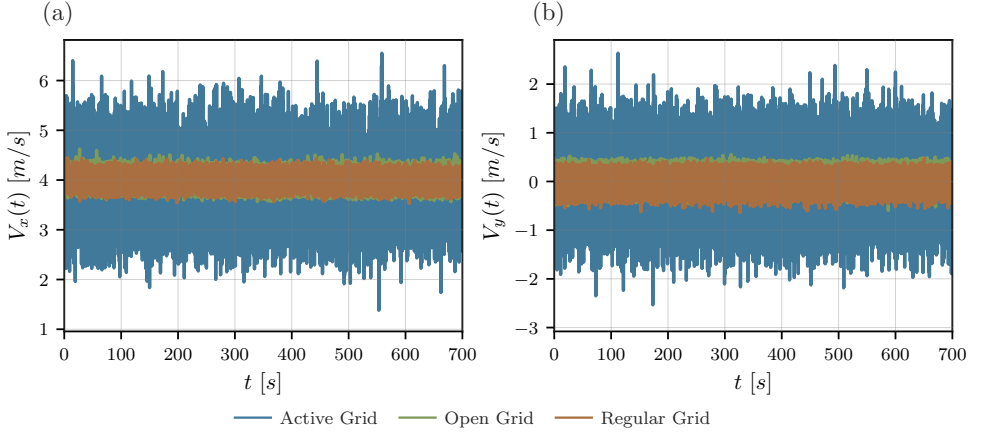


Figure 14: Temporal signals of the streamwise (left panel (a)) and the vertical velocity (right panel (b)). One example of temporal PDPA signal is shown for each of the three grids: active grid in blue color, open grid in green and regular grid in red color. The measurements were taken for a volume fraction of $\phi_v = 1.0 \times 10^{-5}$ and an inlet velocity $U_\infty \approx 4.0$ m/s.

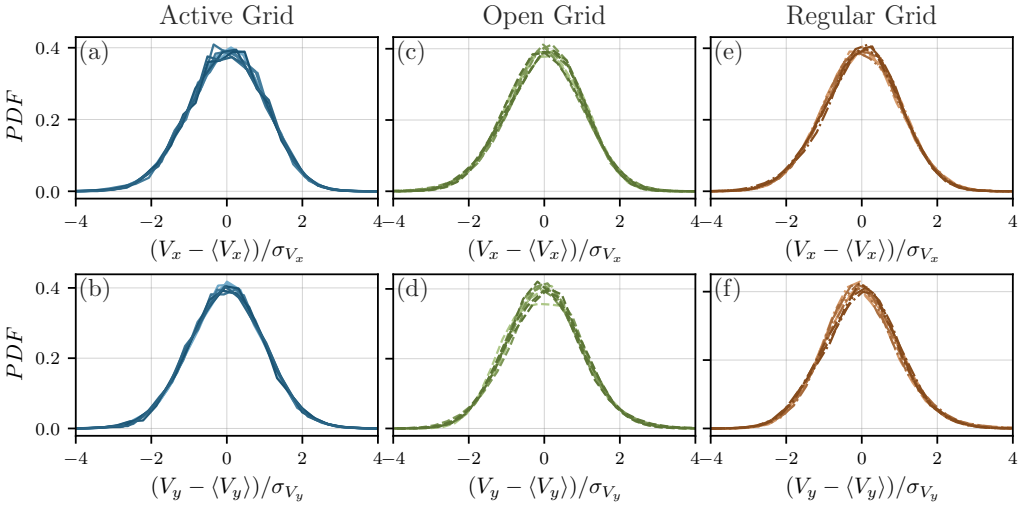


Figure 15: Probability distribution function of the streamwise (top) and vertical (bottom) velocity for each type of grid: active grid (a,b), open grid (c,d) and regular grid (e,f).

831 $V_{XPDPA} \approx \langle U \rangle$ and define the angle-corrected velocity as follow:

$$832 \quad V_{YWT} = V_{YPDPA} - \underbrace{\langle U \rangle \sin(\beta)}_{V_\beta} \quad (C2)$$

833 In order to compute the vertical velocity due to the horizontal component
 834 projection V_β , we estimated the misalignment angle β through measurements of
 835 olive oil droplets settling velocities. We used olive oil to be closer to the limit of
 836 very small diameter and very small volume fraction ϕ_v . Indeed, olive oil droplets

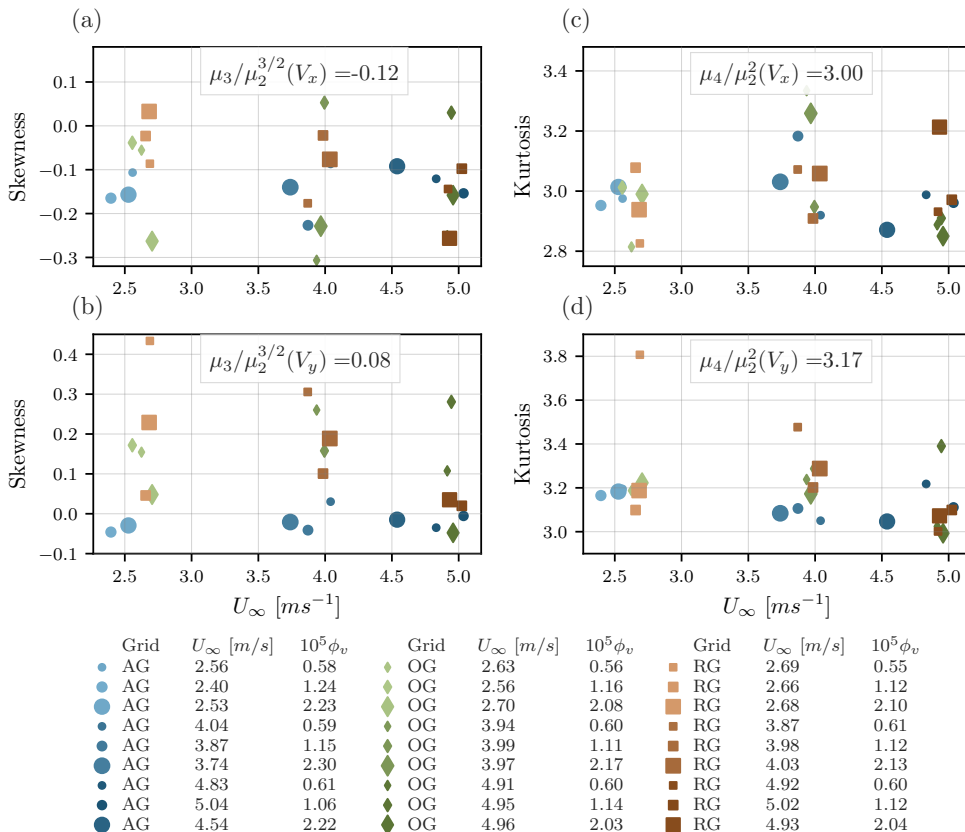


Figure 16: Skewness (left panels) and kurtosis (right panels) of the velocity PDF against the mean streamwise velocity U_∞ . The two top panels shows the moments for the horizontal velocity (a, c) where as the bottom panels correspond to the vertical velocity (b, d). The different symbols (\blacksquare), (\bullet) and (\blacklozenge) represent the regular, active and open grid respectively. The size of the symbol is proportional to the volume fraction and darker colours correspond to higher mean velocities. The quantity given in each panel is the mean value over all the conditions.

837 have a much smaller average diameter, $\langle d_p \rangle \approx 3\mu m$, and a less polydispersed size
 838 distribution than water droplets.

839 The settling velocity of olive oil droplets were collected for different freestream
 840 velocities in absence of grid in order to have a flow as laminar as possible.
 841 Measurements were taken when the probe volume was situated on the center,
 842 close to the wall of the wind tunnel and each time the PDDA had to be realigned.
 843 The particle speed in a still fluid is computed from the particle relaxation time τ_p
 844 including the non-linear drag from Schiller and Naumann semi-empirical equation
 845 (Clift *et al.* 1978),

$$846 \quad V_T = \tau_p g \quad \text{with} \quad \tau_p = \frac{\rho_p d_p^2}{18\mu_f (1 + 0.15 Re_p^{0.687})} \quad (C3)$$

847 With μ_f is the air dynamic viscosity, g the gravitational acceleration, d_p the
 848 particles' diameter, the oil droplet density $\rho_p = 900 \text{ kg.m}^{-3}$ and $Re_p = V_T d_p / \nu$

849 the particle Reynolds number. As the diameter of olive oil droplets is extremely
 850 small the actual velocity is supposed to be equal to the Stokes velocity $V_{YWT} = V_T$.
 851 We then get from equation C 2:

$$852 \quad \langle V_{YPPDA} \rangle = V_T + \langle U \rangle \sin(\beta) \quad (C 4)$$

853 With several freestream velocities and equation C 4 a least squares polynomial
 854 fit on the values of $\langle V_{YPPDA} \rangle$ and $\langle U \rangle$ can be performed to estimate $\sin(\beta)$.
 855 Figure 17 shows $\langle V_{YPPDA} \rangle$ against $\langle U \rangle$ for the probe volume on the center where
 856 a linear fit was done and the slope gives the value of $\sin(\beta)$. In our case, β is
 857 found equal to $\beta = 1.5^\circ \pm 0.3^\circ$.

858

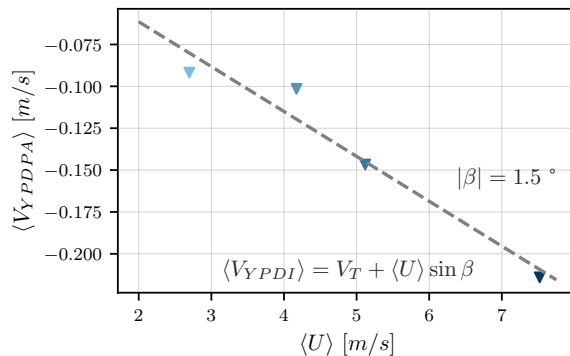


Figure 17: $\langle V_{YPPDI} \rangle$ against $\langle U \rangle$ for the different incoming velocities with olive oil droplets measurements. A linear fit of the data is shown in dashed line.

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