Reynolds number scaling of inertial particle statistics in turbulent channel flows

Matteo Bernardini

Dipartimento di Ingegneria Meccanica e Aerospaziale
Università di Roma "La Sapienza"

Paolo Orlandi's 70th birthday
VORTICAL STRUCTURES AND WALL TURBULENCE
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Motivations

Turbulent flows laden with solid particles common in nature and technology

- Transport and sedimentation processes
- Atmospheric dispersion of pollutants
- Particles droplets in steam turbines
- Transport of chemical aerosols

Inertial particles in wall-bounded flows

Preferential concentration (particle clustering)

- Inertial particles cannot follow the instantaneous fluid flow streamlines
- Low particle concentration found in the cores of strong vortices

Turbophoretic drift

- Strong segregation of particles in the near wall-region
- Net mass transfer against a gradient in turbulence intensity

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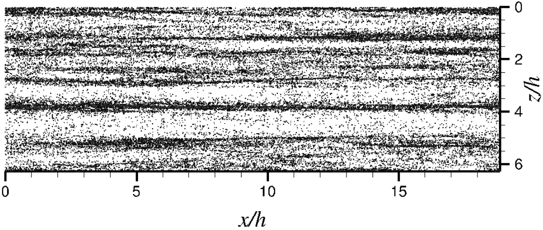
Turbophoresis



Turbophoretic drift

- Preferential concentration in the spanwise direction
- Particle transfer driven by the action of strong ejections and sweeps (Marchioli & Soldati, JFM 2002)
- Only intermediate-size particles affected by turbophoresis

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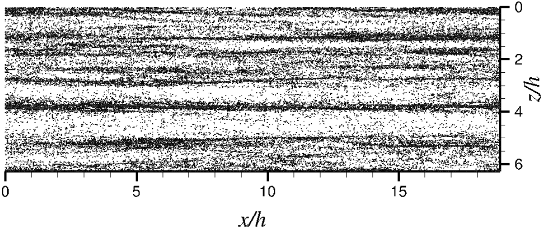

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Background and objectives

Background

- Experimental difficulties (high particle concentration in the viscous sublayer)
- Most analysis made using DNS coupled with Lagrangian particle tracking
- Previous studies limited to low Reynolds numbers ($Re_\tau = 150 - 300$)

Main goal

- Understand the effect of the Reynolds number
- Key open questions:
  - is the turbophoretic drift universal with the Reynolds number?
  - what's the effect of the Reynolds number on the particle deposition rate?

- DNS up to $Re_\tau = 1000$!

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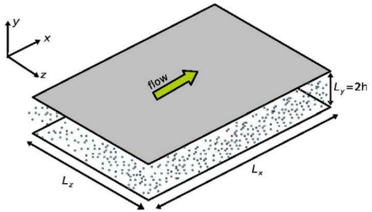
Numerical methodology

Carrier phase



- Solution of NS equations for a solenoidal velocity field
- Second-order FD solver on staggered mesh (provided by Orlandi)
- Discrete kinetic energy preservation
- Simulations performed in convecting frame (Bernardini et al. 2013)
- Doubly-Cartesian MPI splitting (x-z → best choice for load-balance)

Numerical methodology

Particle phase

Particle equations

- Diluted dispersion of pointwise, spherical particles $\rightarrow$ one-way coupling
- Heavy particles, density ratio $\rho_p/\rho_f \approx 2700$ (sand in air)
- Motion of a small rigid sphere described by Maxey and Riley (PoF 83)
- Forces neglected: added mass, fluid acceleration, Basset history force, gravity

$$\begin{aligned} \frac{\mathrm{d}\mathbf{x}_p}{\mathrm{d}t} &= \mathbf{u}_p \\ \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t} &= \frac{k_p}{\tau_p}\left(\mathbf{u} - \mathbf{u}_p\right) \end{aligned} \quad (1)$$

- Particle relaxation time $\tau_p = \rho_p \, d_p^2/18\mu$ (measure of inertia)
- Stokes number $St = \tau_p/\tau_f \rightarrow St = \tau_p \, u_\tau^2/\nu$

Physical and computational parameters

Flow case	Re_τ	N_x	N_y	N_z	Δx^+	Δz^+	Tu_τ/h	T^+
P150	145	384	128	192	7.1	4.7	657	95265
P300	299	768	192	384	7.3	4.9	410	122590
P550	545	1280	256	640	8.0	5.3	326	177670
P1000	995	2560	512	1280	7.3	4.8	170	169150

Table : List of parameters for particle-laden turbulent channel flows.

St	d_p^+	$d_p(\mu m)$	$\tau_p(s)$	ρ_p/ρ_f
1	0.082	1.0	$9.55 \cdot 10^{-6}$	2700
10	0.25	3.2	$9.55 \cdot 10^{-5}$	2700
25	0.41	5.0	$2.39 \cdot 10^{-4}$	2700
100	0.82	10.0	$9.55 \cdot 10^{-4}$	2700
500	1.83	22.4	$4.78 \cdot 10^{-3}$	2700
1000	2.58	31.6	$9.55 \cdot 10^{-3}$	2700

Table : Relevant parameters for the inertial particles

Analysis of particle dispersion

Shannon entropy

How quantify the wall accumulation process?

- Shannon entropy parameter: single global indicator

Entropy parameter estimation

- Slice the box in M slabs
- Compute $p_j = N_j/N, j = 1, \ldots, M$
- Entropy: $S = \frac{-\sum_{j=1}^{M} p_j \log p_j}{\log M}$
- $S = 0 \rightarrow$ particles into a single slab
- $S = 1 \rightarrow$ uniform distribution

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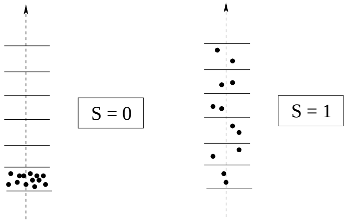
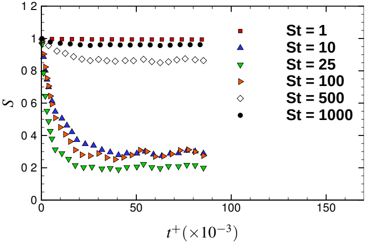
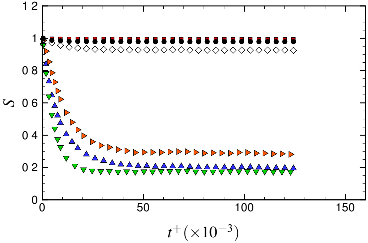


Particle dispersion (Shannon entropy evolution)

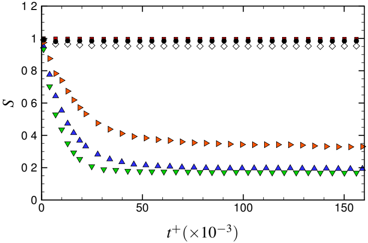
P150



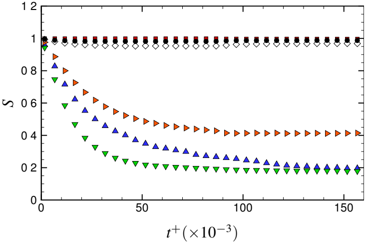
P300



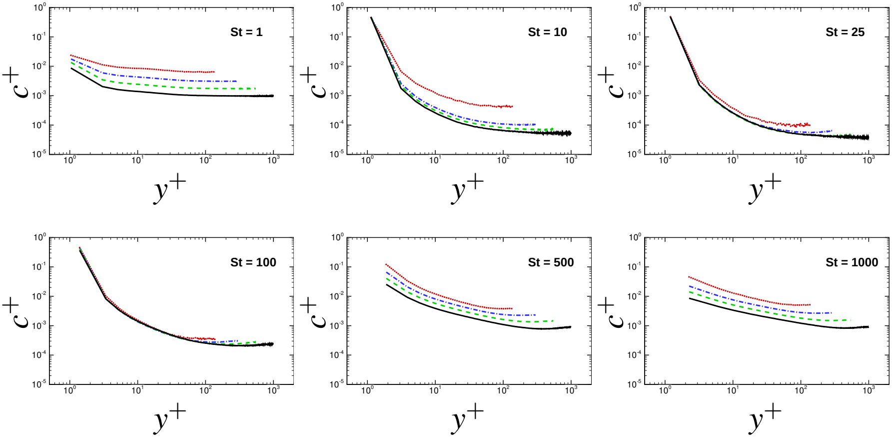
P550



P1000



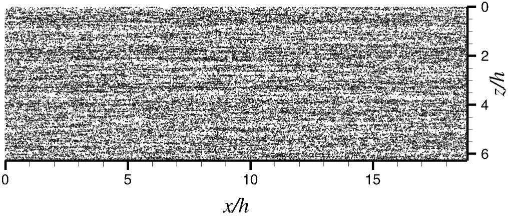
Wall-normal concentration profiles



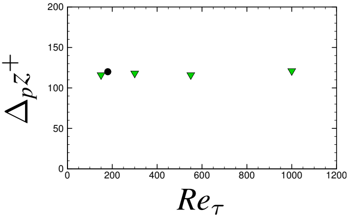
- Lines: $Re_\tau = 150$; $Re_\tau = 300$; $Re_\tau = 550$; $\boldsymbol{Re_\tau} = 1000$.

Spatial organization

- Instantaneous distribution of $St = 25$ particles at $Re_\tau = 1000$



- Spanwise spacing of the particle streaks at ($St = 25$)



Deposition rate

Deposition coefficient

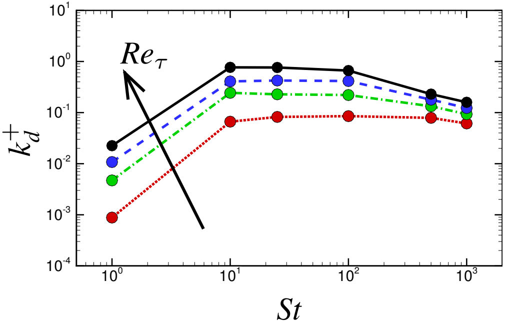
- The rate at which particle deposit is fundamental for practical purposes
- particle mass transfer rate at the wall $J = \mathrm{d}N/\mathrm{d}t/A_d$
- bulk concentration $C = N/\phi$
- In the case of channel flow

$$k_d = -J/C = \frac{h}{N}\left|\frac{\mathrm{d}N}{\mathrm{d}t}\right| \tag{2}$$

- k_d has dimension of velocity

$$k_d^+ = \frac{1}{N}\left|\frac{\mathrm{d}N}{\mathrm{d}t}\right|\frac{h}{u_\tau} \tag{3}$$

Deposition coefficient



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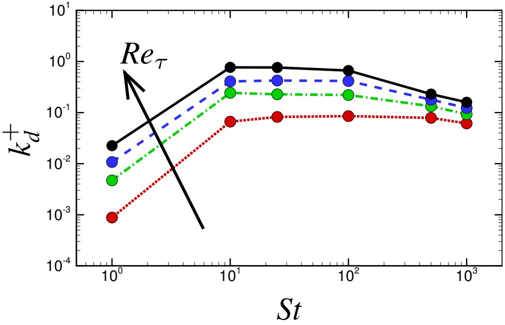

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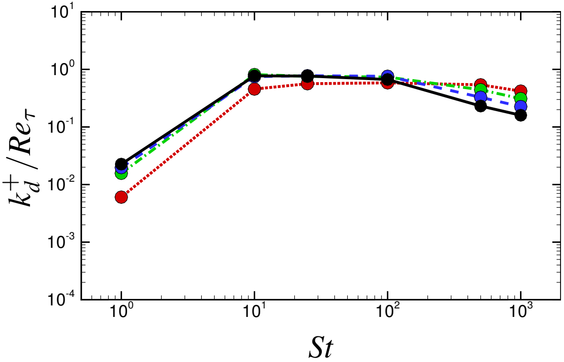
Deposition coefficient

Inner-scaling

- Deposition rate of segregated particles collapse in inner units



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Conclusions

- DNS of particle-laden turbulent channel flows up to $Re_\tau = 1000$
- Particle St numbers in the range $St = 1 - 1000$
- Universality of the turbophoretic drift
- Particle concentration curves collapse in inner-scaling
- Spanwise spacing of particle streaks constant with Re_τ
- Inner-scaling to collapse the deposition rate of segregated particles

Reference

- M. Bernardini, *Reynolds number scaling of inertial particle statistics in turbulent channel flows*, JFM-RP 2014, in press

Acknowledgments

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