A Stochastic Approach to Modeling Subgrid Velocity Fluctuations in Large Eddy Simulation of Turbulent Wall-Bounded Particle-Laden Flows

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Turbulent particle-laden flow

Aerosol in exhaled breath or sneeze

Sediment transport in rivers

blood flow (plasma (liquid), red blood cells(solid))

Air pollution

Volcanic eruptions

Rain formation in clouds

Sand and dust storms

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Turbulent particle-laden flow

Study of turbulent particle-laden flows

Experimental →

- Useful physical information.
- Data can be used to validate the numerical solver.
- Sometimes hard to perform.
- Expensive and time consuming.

Numerical →

- Robust numerical algorithms are needed (ongoing topics of research).
- Effect of different parameters can be studied.
- Behaviors of the flow can be predicted
- The design optimization can be performed.

Solver and computational domain

Numerical simulation

Eulerian-Lagrangian method
With point-particle assumption

- High accuracy

To resolve the dispersed phase at lower mass fractions.

- Simplicity of modeling

The interaction between the phases.

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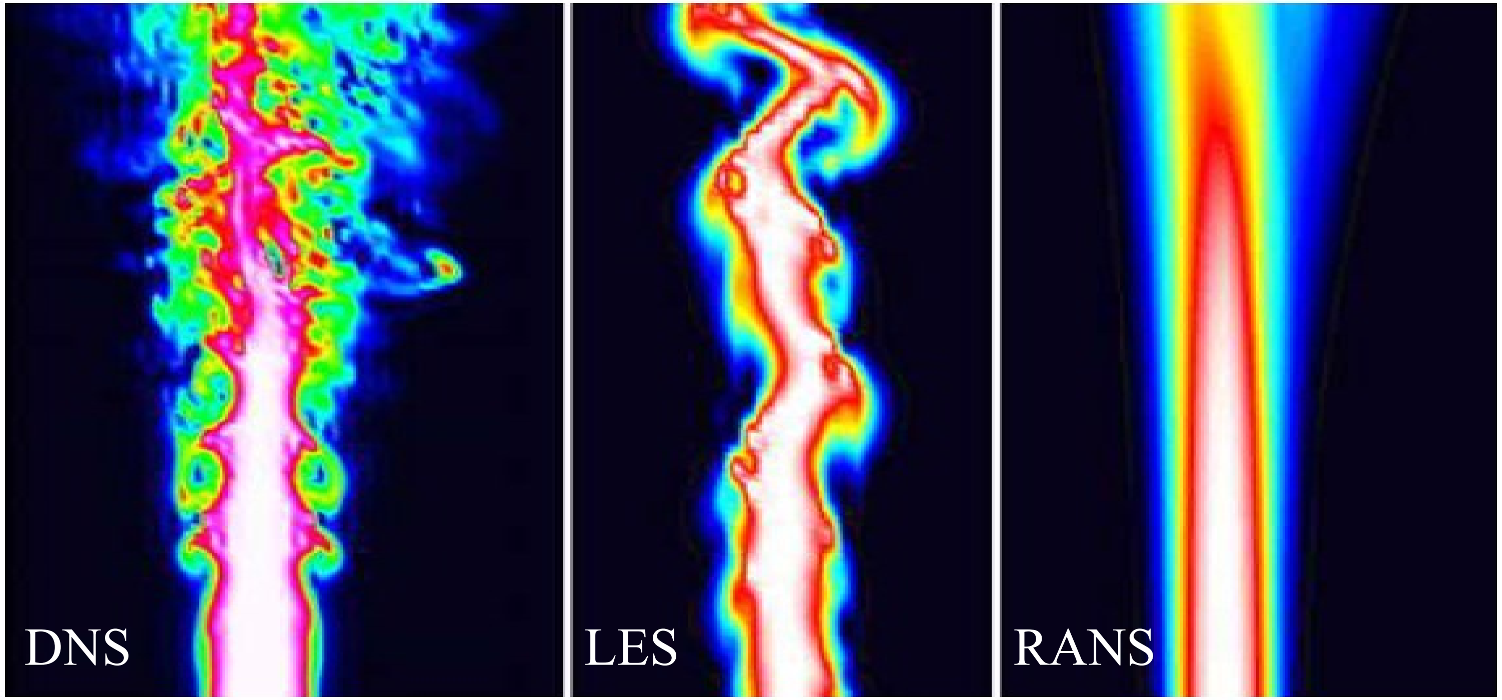
Carrier phase, Eulerian



DNS
- Resolving all of the turbulence scales
- No modeling
- Computationally expensive

LES
- Resolving large scales
- Sub-grid Scale stresses are model
- Trade-off between accuracy and computational cost

RANS
- Mean quantities of fluid flows
- Reynolds stress terms are model
- Lowest computational cost

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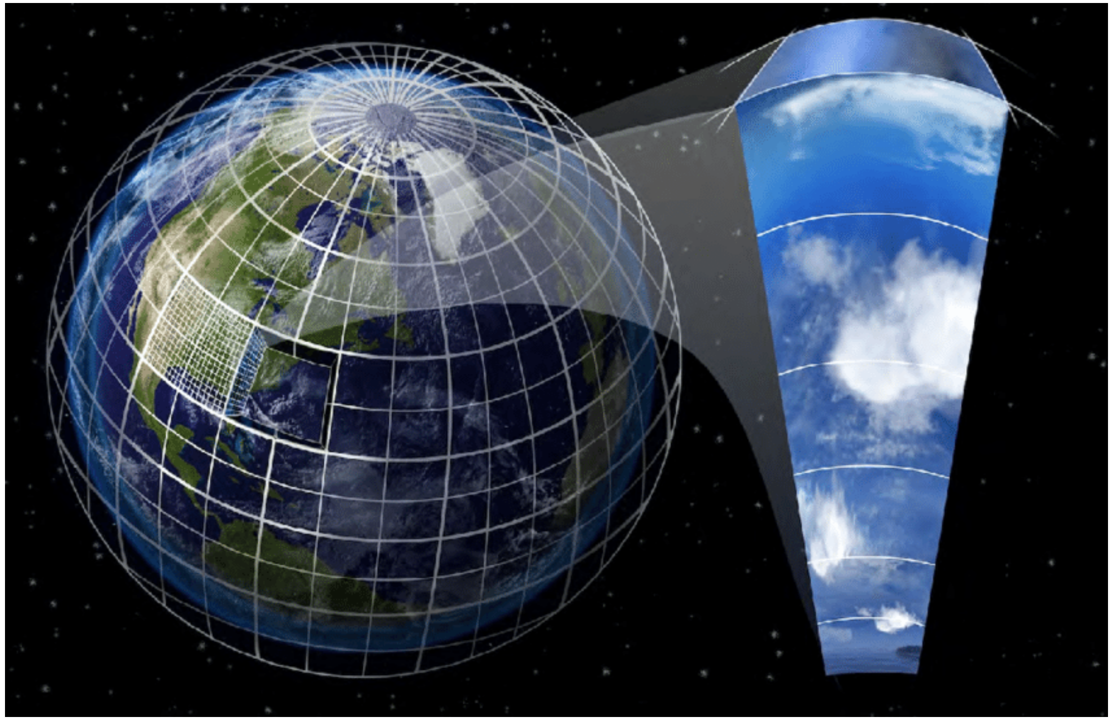
Maries, Adrian, et al. "Interactive exploration of stress tensors used in computational turbulent combustion." New Developments in the Visualization and Processing of Tensor Fields."

LES – Coarse grids

Grid spacing in today's highest-resolution operational global models in atmospheric science is in the order of 10 km



Importance of SGS fluctuations seen by dispersed phase

Lukas, Jeffrey & Barsugli, Joseph & Wolter, Klaus & Rangwala, Imtiaz & Doesken, Nolan. (2014). Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation.

Motivation and Objective

- To develop a computational model for accurately predicting the particle dispersion and deposition in turbulent channel flow. Also, to assess the influences of the particle-wall collision mechanisms, shear-induced lift force, gravity and particle Stokes number. To validate the computational model against the experimental data and DNS results.

- To assess the importance of sub-grid scale (SGS) velocity fluctuations on particle dispersion and disposition .

- To develop a model for SGS velocity fluctuations to improve the accuracy of the large eddy simulation in prediction of particle dispersion and deposition.

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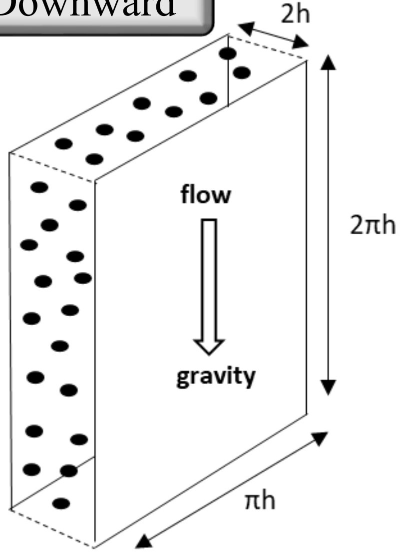
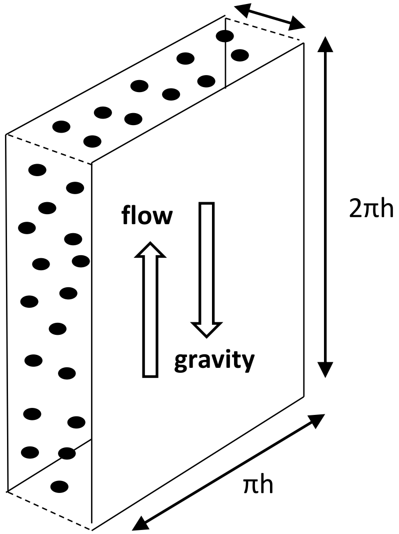
Simple geometry – channel flow

- DNS/LES for carrier phase coupled with Lagrangian particle tracking.
- Point-particle assumption, one-way coupling.
- Vertical channel flowing downward/upward.
- The dimensions of $2\pi h$, $2h$, πh with h being the channel half width.
- No-slip B.C for walls and periodic boundary condition for others.
- Re_τ= 180 - tracking 200,000 particles.
- Particle-wall collisions: fully elastic (elastic-wall) or fully absorbing (trap-wall).
- For DNS 128^3 grid points, and for LES 32^3.
- The parallel solver runs in a distributed memory environment (MPI).

Downward





Upward

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Particles characteristic

$$\text{Stokes number} = \frac{\tau_p}{\tau_f} = \frac{\text{Relaxation time for particle velocity}}{\text{Fluid time scale in wall units}} = \frac{\frac{\rho_p d_p^2}{18\mu}}{\frac{\nu}{u_\tau^2}}$$

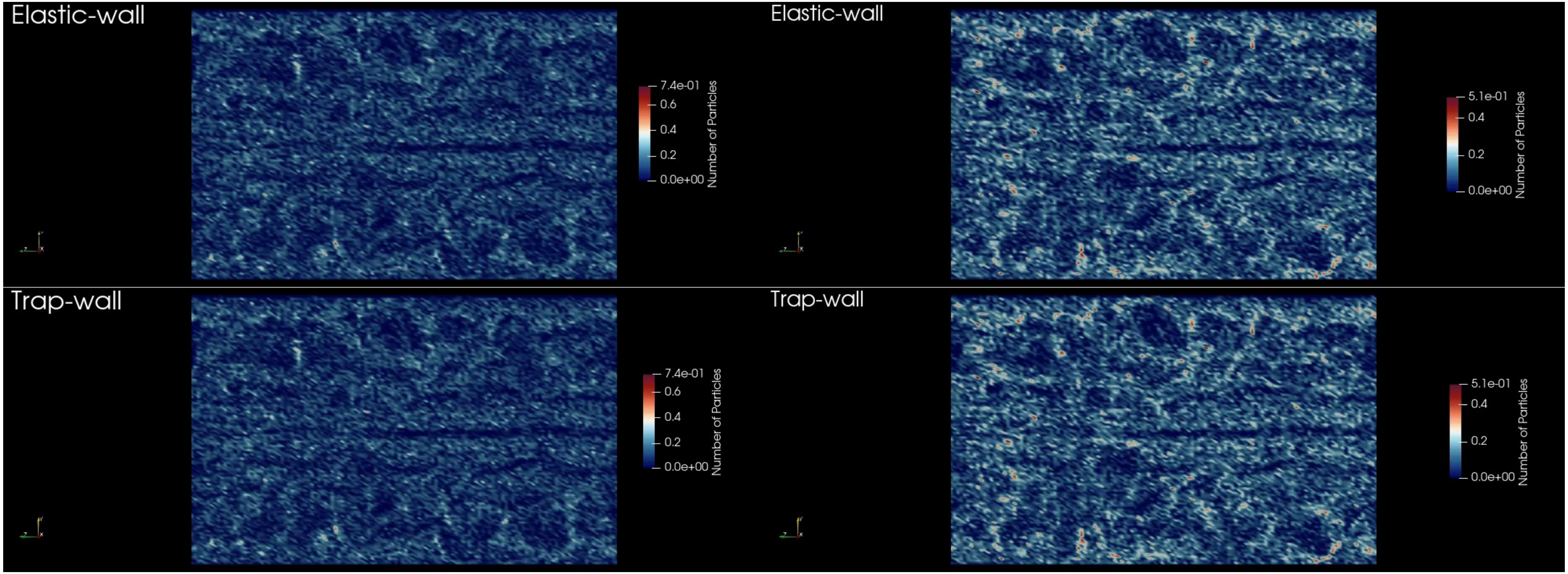
Nondimentional settling velocity

$$\frac{U_s}{U_c} = \frac{W_p}{F_d} = \frac{g d_p^2 \rho_p}{18\mu U_c}$$

St	$d_p/h[10^{-4}]$	d_p^+	U_s/U_c	U_s/u_τ
1	5.6	0.101	0.003	0.054
2	7.6	0.137	0.0058	0.113
5	12	0.216	0.0147	0.272
10	16.8	0.302	0.029	0.545
24	26	0.468	0.070	1.31
32	30	0.54	0.095	1.74
64	42	0.756	0.185	3.43
100	53	0.954	0.294	5.45
130	60	1.08	0.383	7.08

Particles motion

Spanwise-normal (Z-Y) plane



St = 5

St = 100

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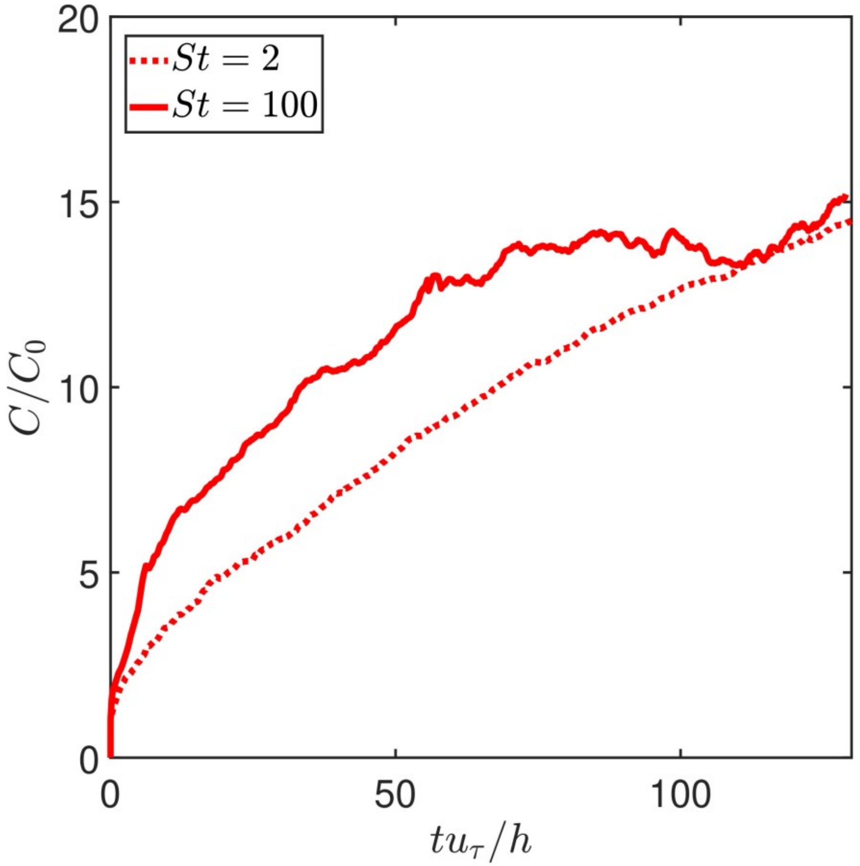
ParaView

Elastic-wall assumption

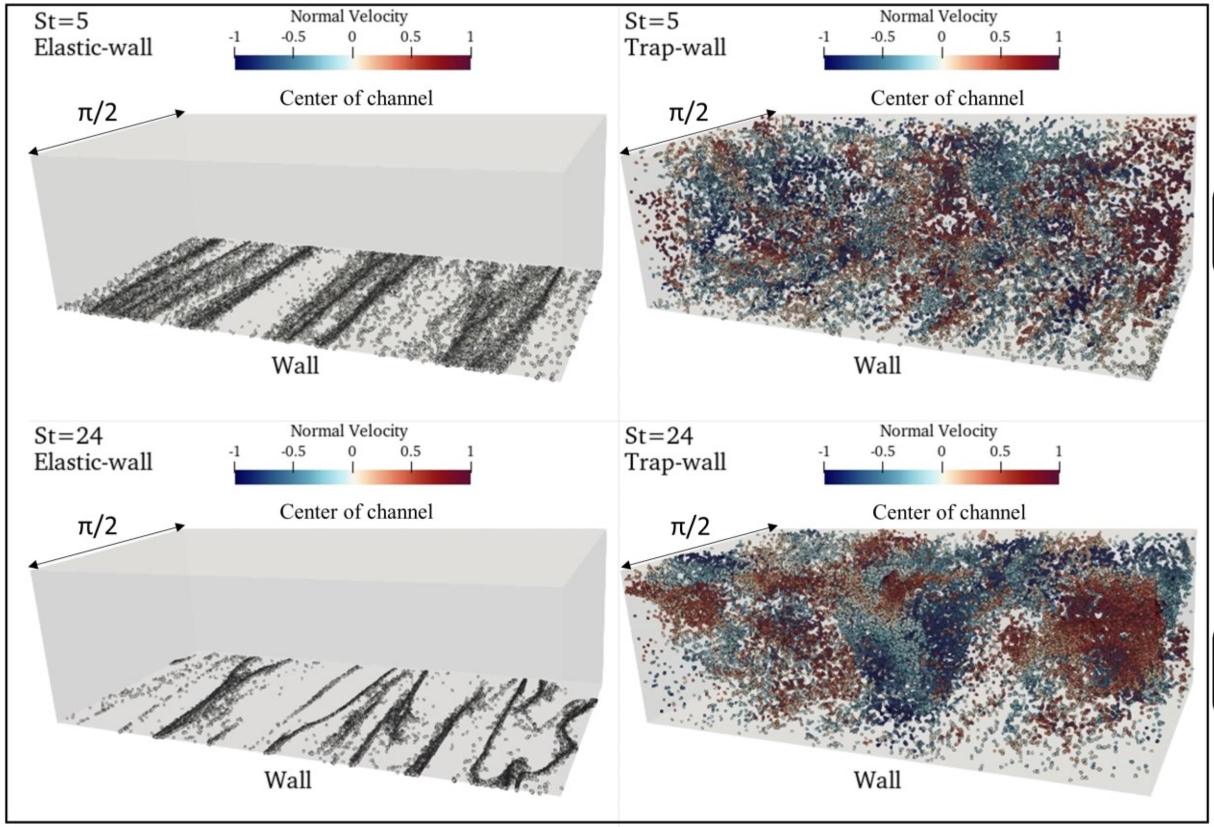
Concentration in near wall region



Steady migration of particles toward the walls

Elastic-wall

Trap-wall



St = 5

St = 24

Snapshot of particle dispersion $tu_\tau/h = 200$

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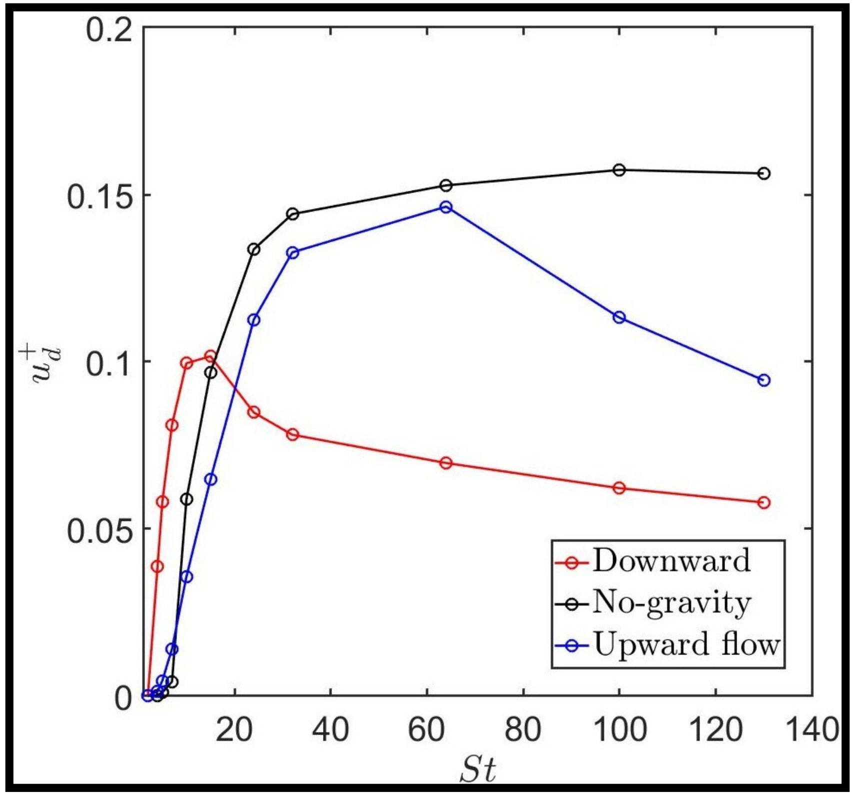
Variation of deposition velocity with Stokes number

Deposition velocity

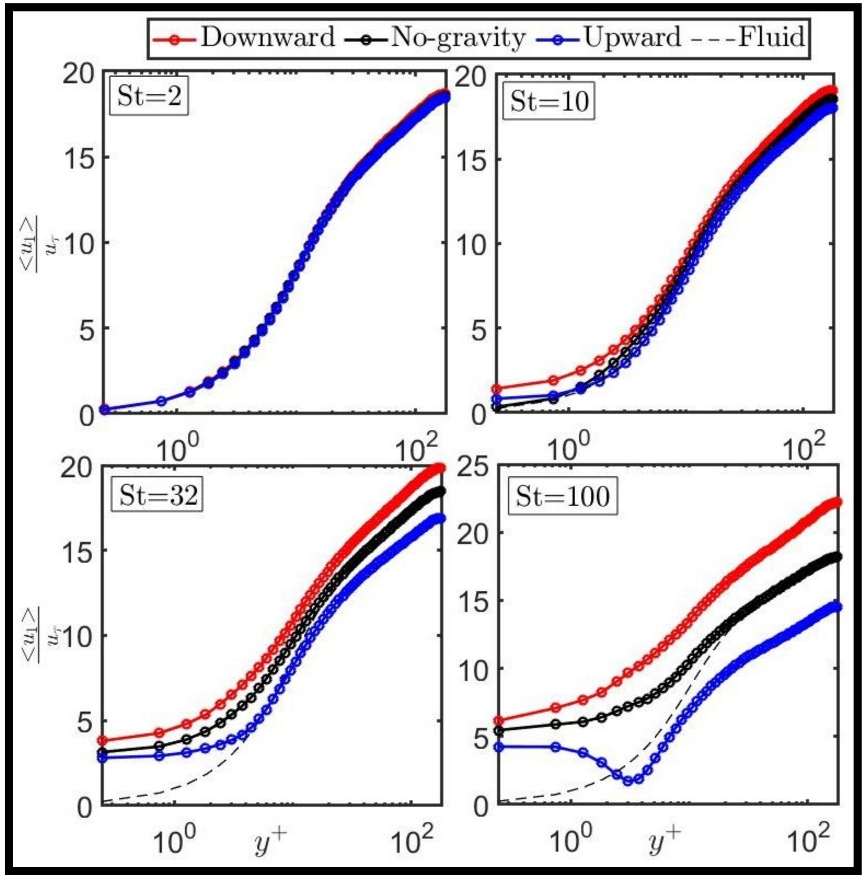


Unexpected behavior for high Stokes number

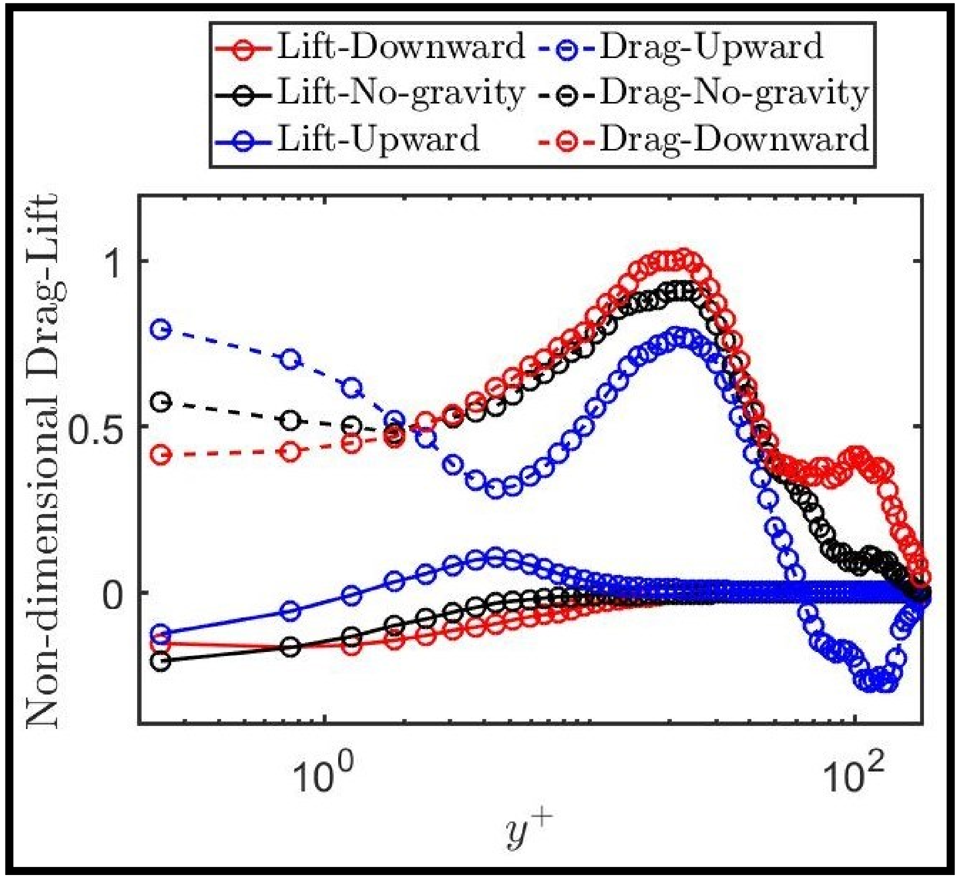
- St < 20 : Higher deposition velocity for downward flow
- St > 20 : Lower deposition velocity for downward flow

Lift force direction

Streamwise velocity



Lift force
St=32



- Lift Force: $F_{L_2} = -\frac{2.5}{\pi}\rho_f \nu^{(1/2)} d_p^2 (u_1 - v_1) \left|\frac{du_1}{dx_2}\right|^{0.5} \operatorname{sgn}\left(\frac{du_1}{dx_2}\right) J^n$

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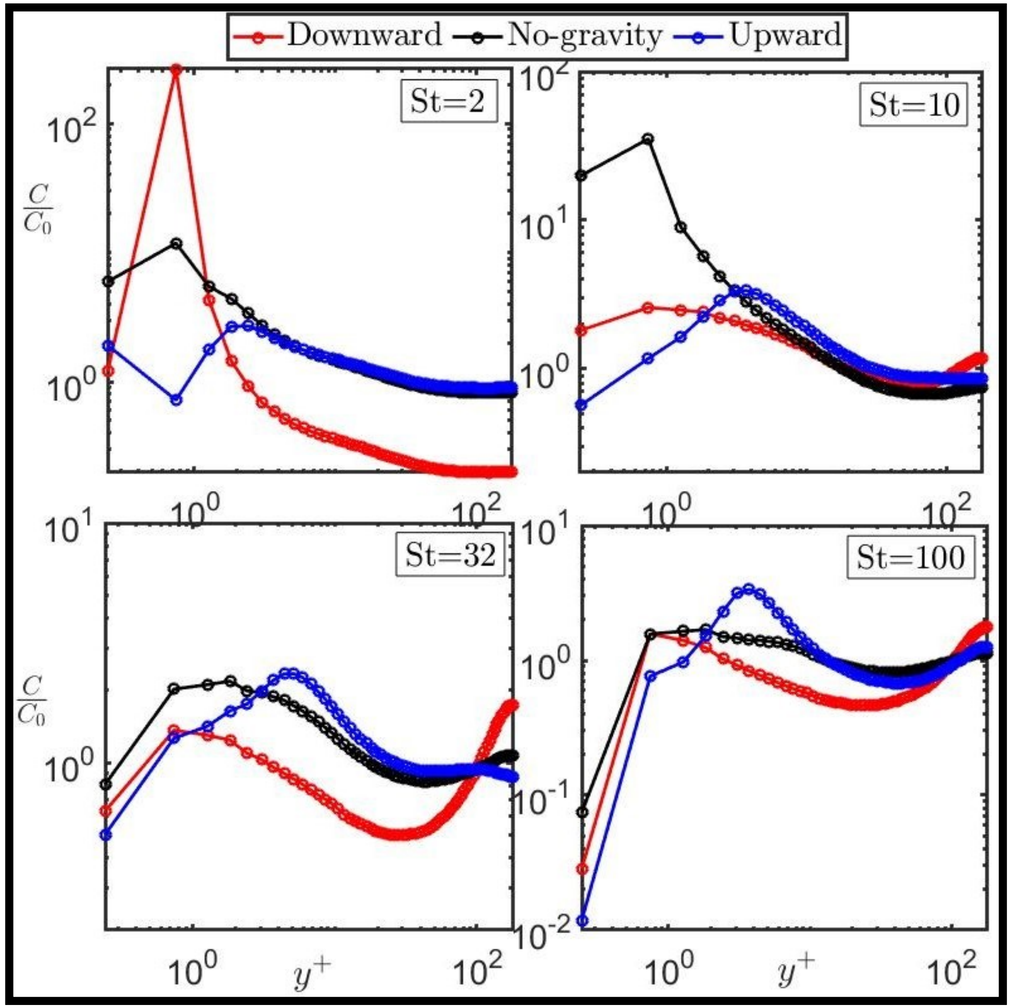
Concentration of particles



@ $y^+ \simeq 10$: high normal velocity fluctuation + higher concentration = higher deposition velocity

Recent publication of DNS results

Rousta, F., Lessani, B. and Ahmadi, G., 2023. Particle dispersion and deposition in wall-bounded turbulent flow. International Journal of Multiphase Flow, 158, p.104307.

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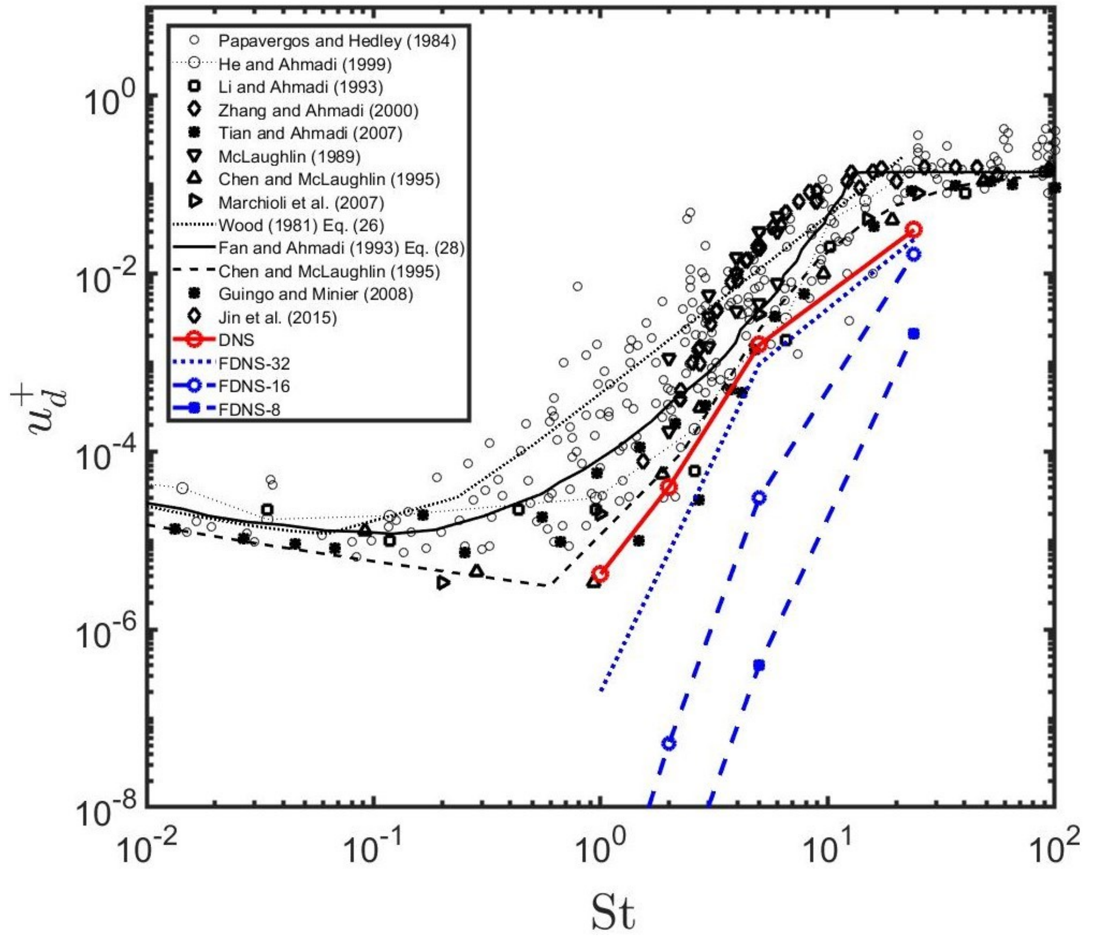
LES vs DNS - deposition velocity

Deposition velocity



Considerable difference especially for Lower Stokes number at higher Reynolds number

LES vs DNS – Stochastic modeling

SGS velocity fluctuation see by particles

$$\frac{du_i'}{dt} = -\alpha u_i' + \lambda \xi_i$$

$$u_2'^{n+1} = \frac{\sigma_2^{n+1}}{\sigma_2^n} u_2'^n \exp\left(-\frac{\Delta t}{\tau_2}\right) + \sigma_2^{n+1}\left(1 - \exp\left(-2\frac{\Delta t}{\tau_2}\right)\right)^{\frac{1}{2}} \xi_2 + \frac{\tau_2}{1+St}\frac{\sigma_2^{n+1}\partial\sigma_2^{n+1}}{\partial y}\left(1 - \exp\left(-\frac{\Delta t}{\tau_2}\right)\right)$$

- τ is Lagrangian time scale
- σ is RMS of SGS velocity fluctuation

- $\tau \approx \Delta/(K_{SGS})^{1/2}$

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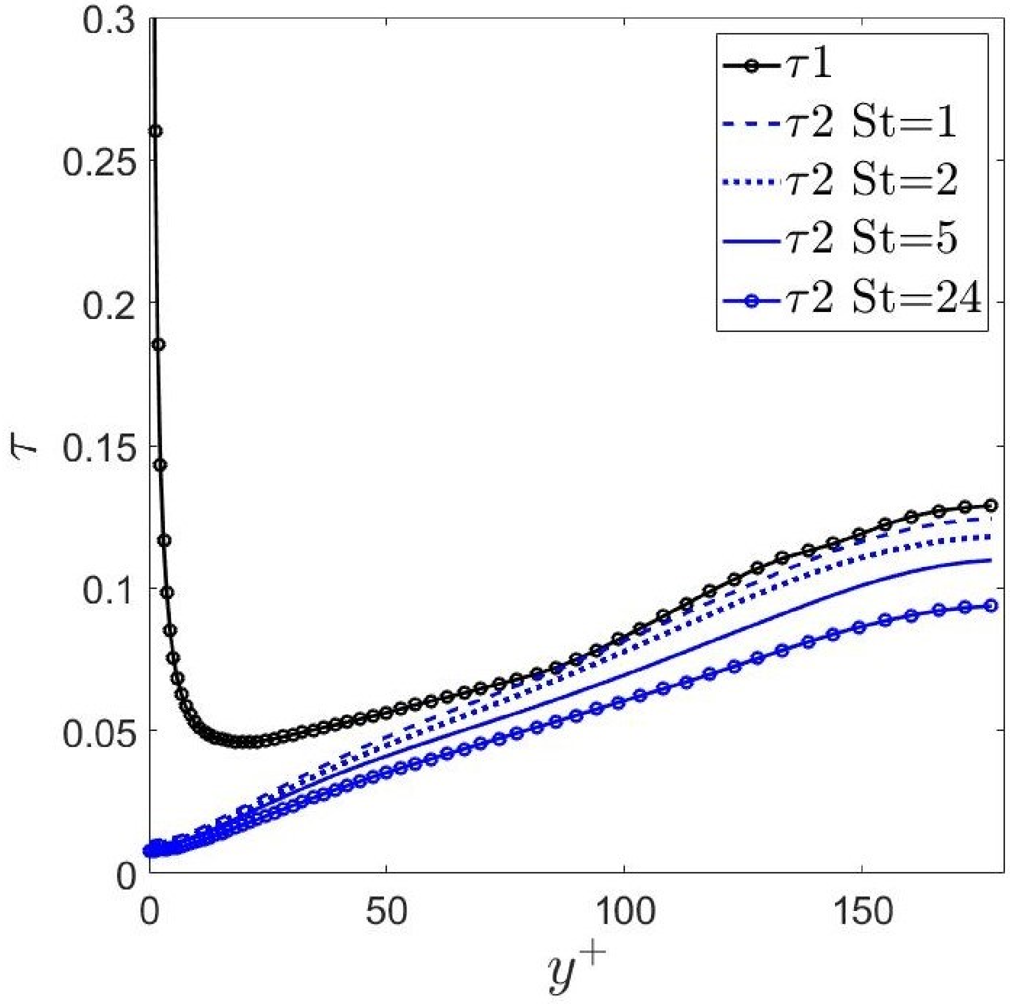
Lagrangian time scale (τ)



- $\tau_1 = \dfrac{\Delta}{2\pi^{1/3}(2/3K_{SGS})^{1/2}}$

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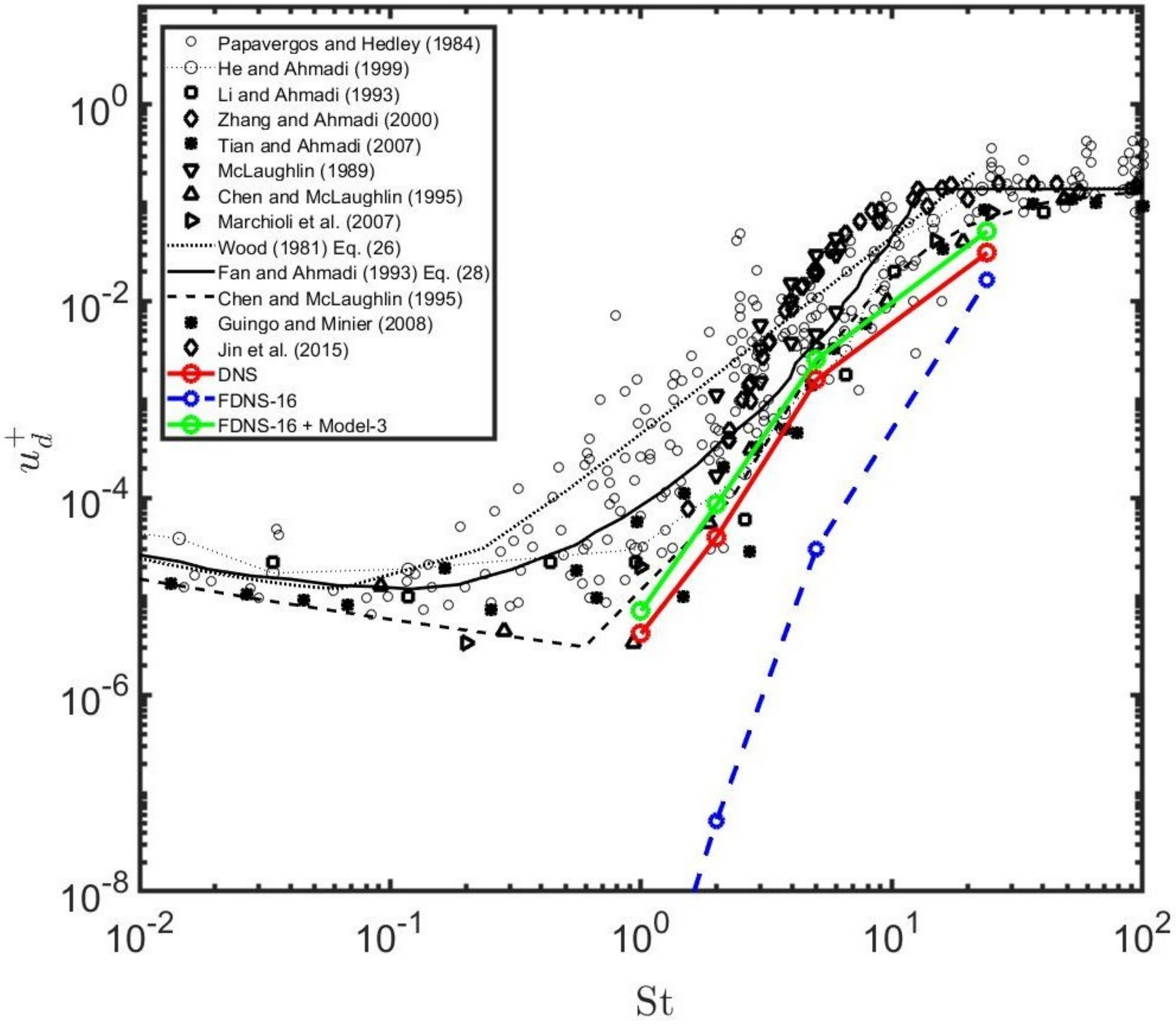
Deposition velocity with subgrid-scale model



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Conclusions and future study

- Concentration of larger particles in the buffer layer increases the particle deposition rate.
- Neglecting SGS fluctuation effects on particles significantly the particle dispersion and deposition.
- Using appropriate SGS model improves the deposition velocity predictions of LES.

Future work

- For the next step, the model will be tested for different resolutions of LES and its accuracy will be assessed.

Thank you for your attentions!

Questions?