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Direct Numerical Simulation of Of Dense Gas-Solid Flows Including Particle Collision

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NETL 2011 Workshop On Multiphase Flow Science

Outline

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- Motivation and Objectives
- Governing Equations
- Results

  \- Fluctuation Velocities

  \- Particle Concentration

  \- Particle Deposition Velocity
- Conclusions

Objectives

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Provide insight into the following questions:

- **How the particle and flow turbulence intensities are affected?**
- **How the particle deposition velocity is affected by two-way coupling, particle collisions and four-way coupling?**
- **How the particle-velocity correlations are affected by increase in concentration?**

Direct Numerical Simulations

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Wall Units

$$u_i^+ = \frac{u_i}{u^*}$$

$$x_i^+ = \frac{u^* x_i}{\nu}$$

Navier-Stokes

$$\nabla^+ \cdot \mathbf{u}^+ = 0$$

$$\frac{\partial \mathbf{u}^+}{\partial t^+} + \mathbf{u}^+ \cdot \nabla^+ \mathbf{u}^+ = \nabla^{+2} \mathbf{u}^+ - \nabla^+ P^+ + \mathbf{S}_{\mathbf{u}}^{\mathbf{p}}$$

Spectral Method

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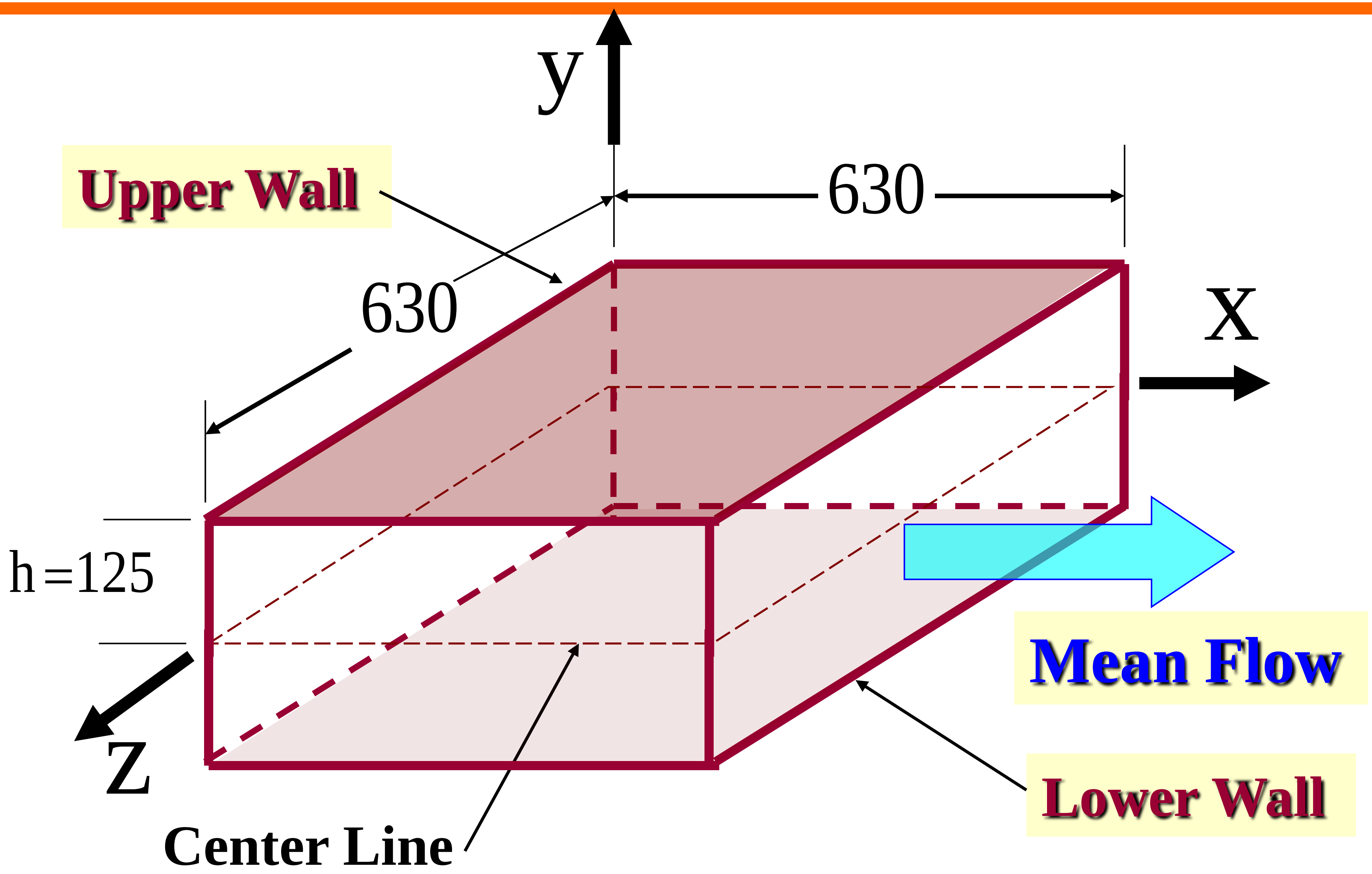
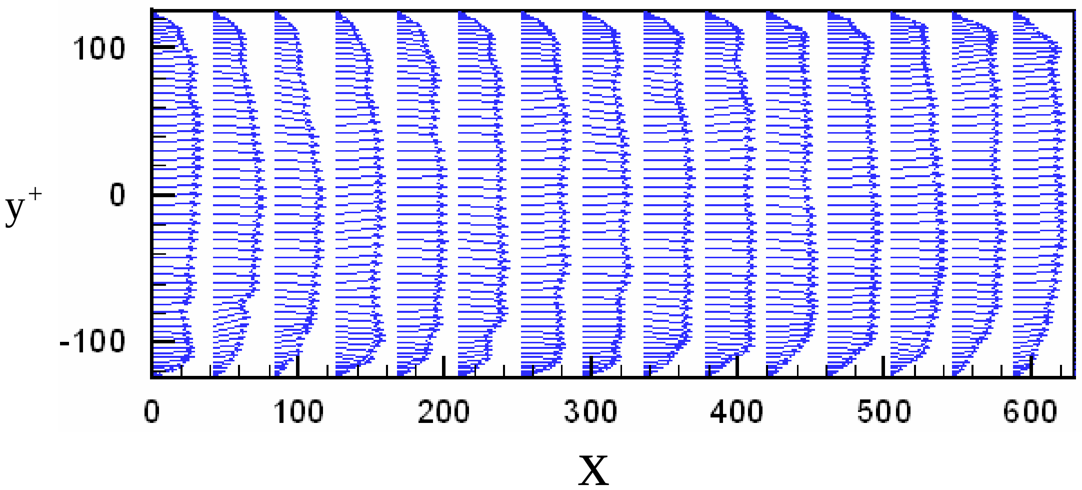
$$\vec{u}(x,y,z,t) = \sum_{l=-\frac{N_x}{2}}^{\frac{N_x}{2}-1} \sum_{m=-\frac{N_z}{2}}^{\frac{N_z}{2}-1} \sum_{n=0}^{N_y} \vec{\tilde{v}}(l,m,n,t)\, e^{2\pi i\left(\frac{lx}{\lambda_x}+\frac{mz}{\lambda_z}\right)}\, T_n\left(\frac{y}{H}\right)$$

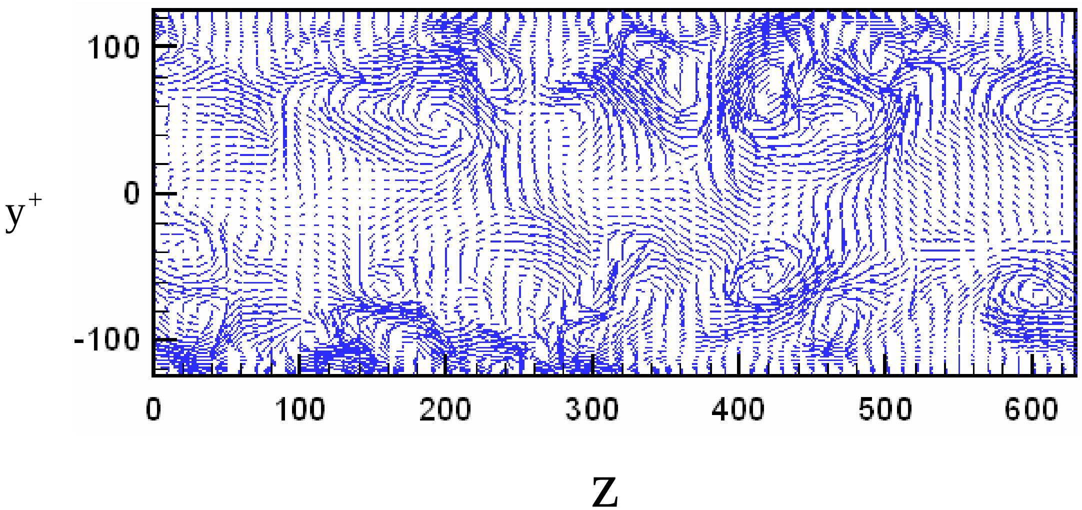
$$T_n\left(\frac{y}{H}\right) = \cos\left(n\cos^{-1}\left(\frac{y}{H}\right)\right)$$

Flow Between Two Parallel Plates

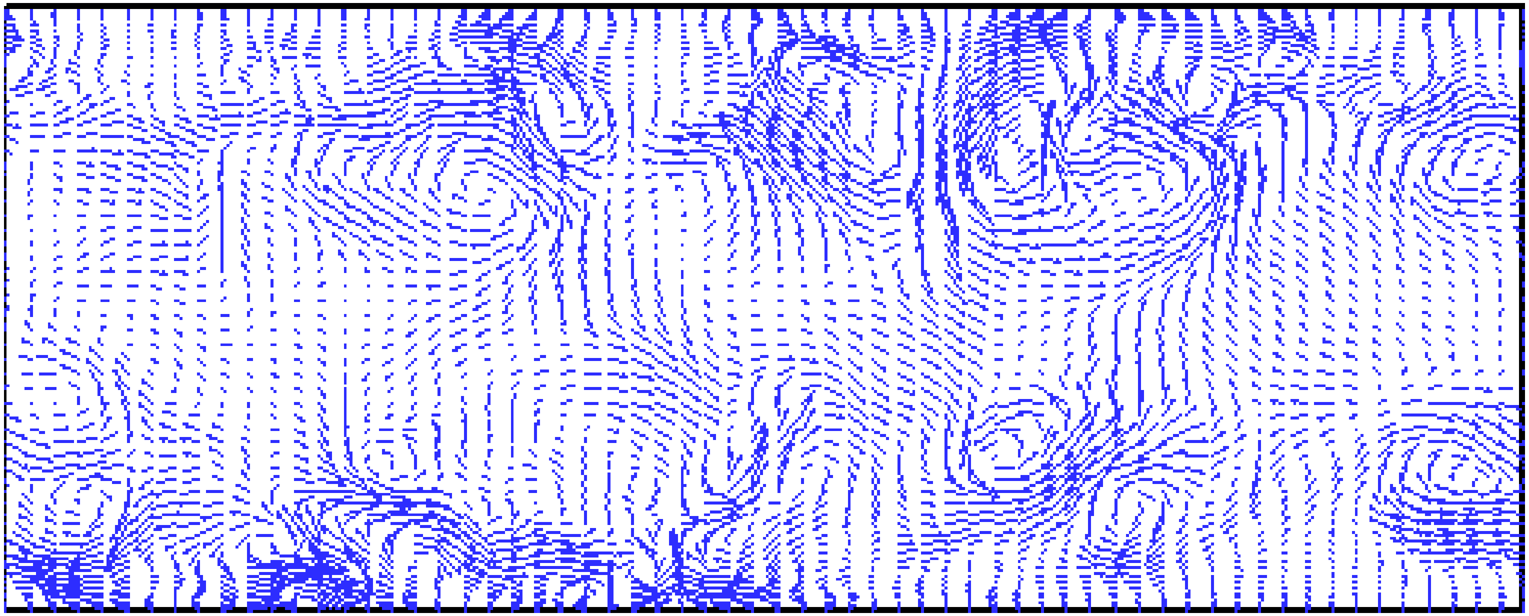


Instantaneous Velocity Field





Flow Field Visualization



Contour Plot of v-Velocity

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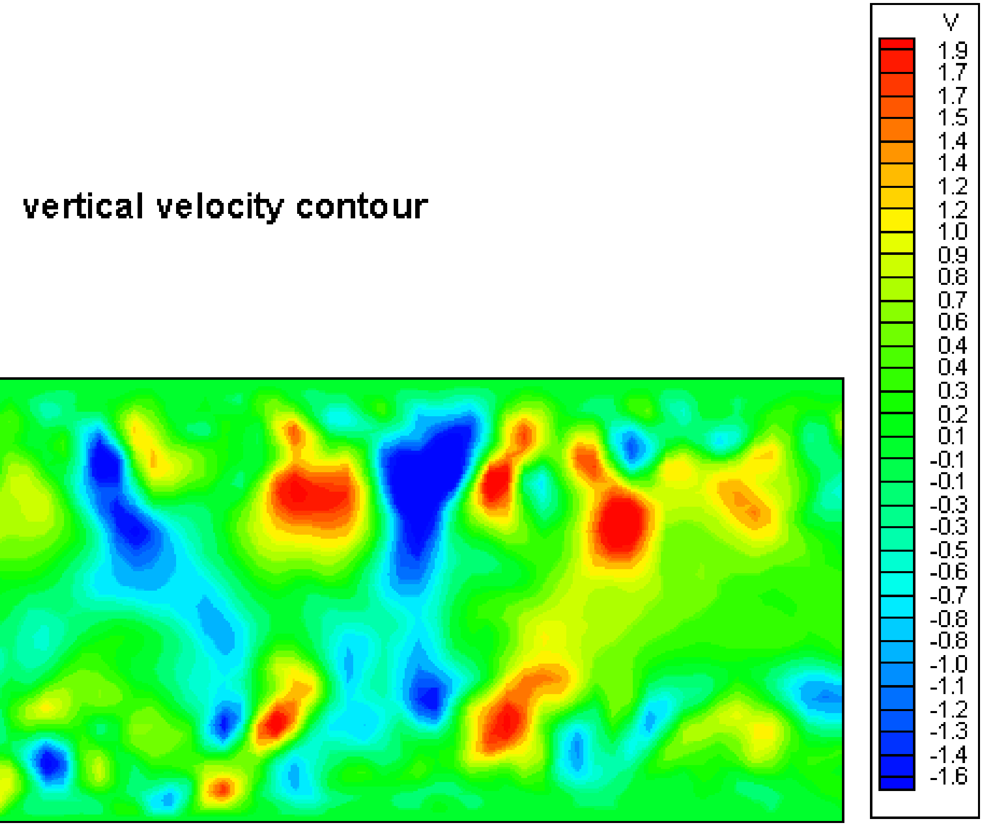

Average Streamwise Velocity

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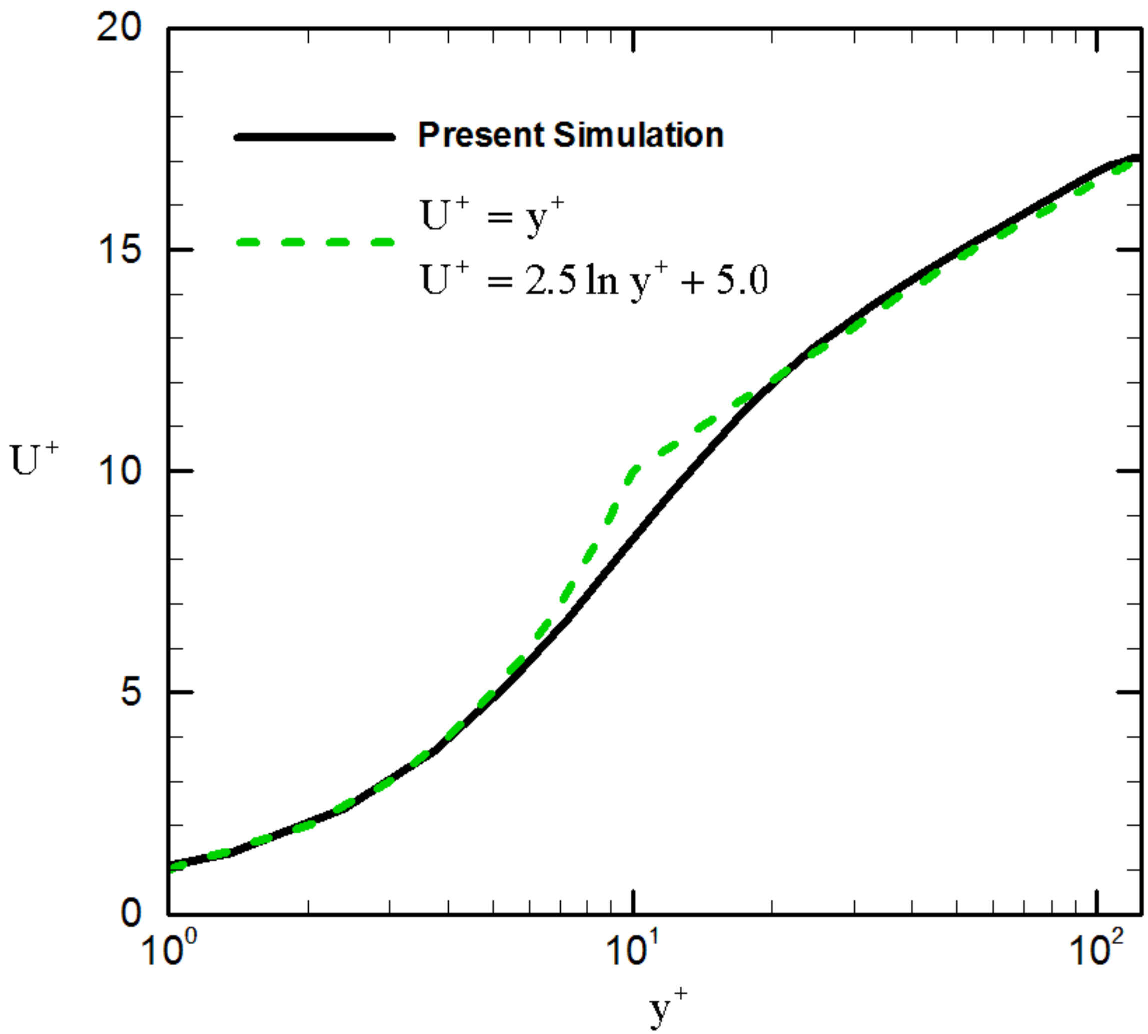

Particle Equations

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$$\frac{d\vec{u}^{+p}}{dt^{+}} = C_D F_d^{+} + F_l^{+} + \vec{n}^{+}(t^{+}) + \vec{g}^{+}$$

$$\frac{d\vec{x}^{+}}{dt^{+}} = \vec{u}^{+p}$$

$$C_D = \begin{cases} 1.0 + 0.1875\,\mathrm{Re}_p & \mathrm{Re}_p \le 0.01 \\ 1.0 + 0.1315\,\mathrm{Re}_p^{\,0.82-0.0217\ln(\mathrm{Re}_p)} & 0.01 \le \mathrm{Re}_p \le 20 \end{cases}$$

Wall units

$$\vec{x}^{+} = \frac{\vec{x}\,u^{*}}{\nu} \qquad t^{+} = \frac{t\,u^{*2}}{\nu} \qquad \vec{u}^{+} = \frac{\vec{u}}{u^{*}}$$

Point Particles approximations, inelastic collisions

Initial Particle Distribution

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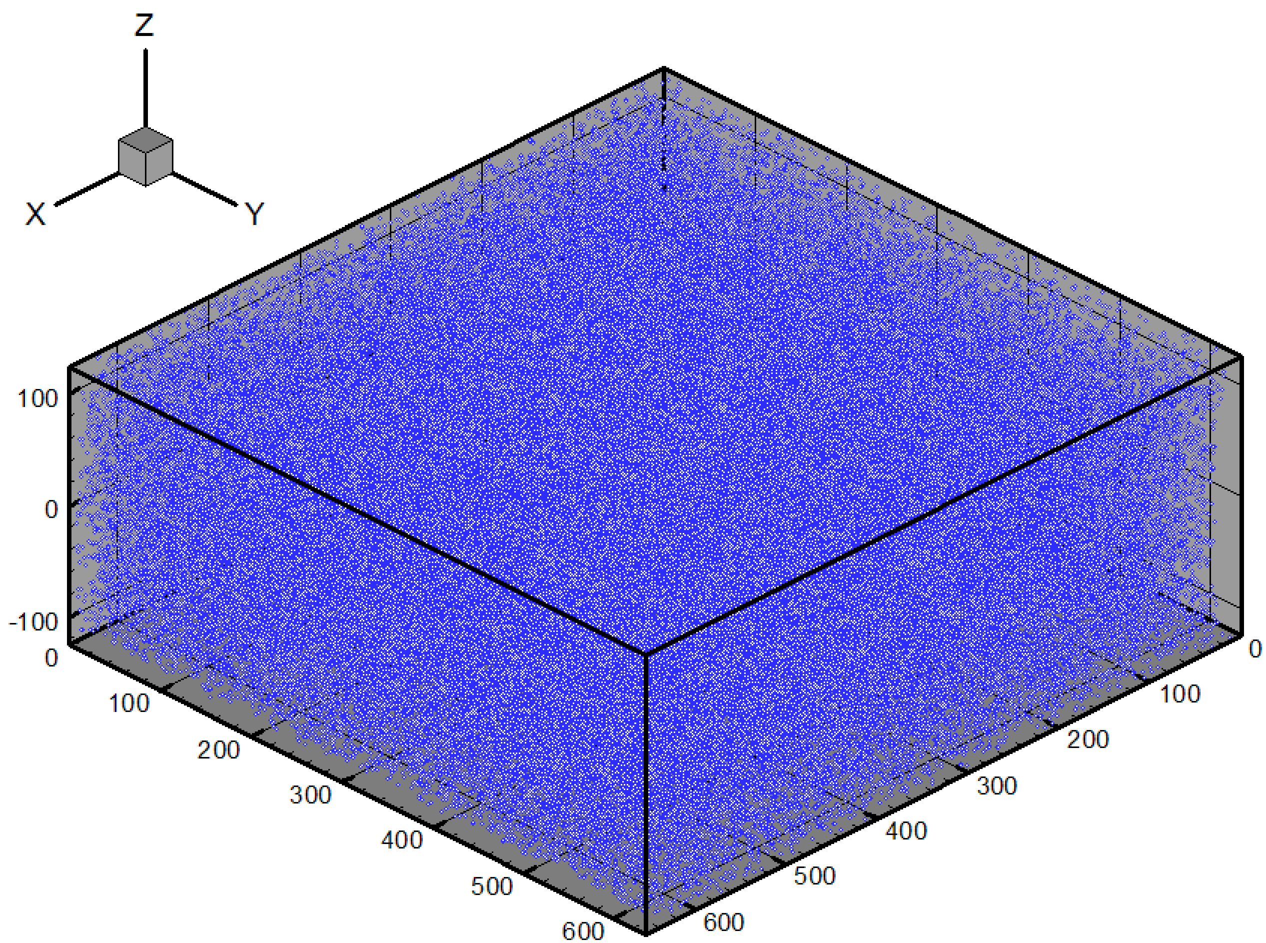

Particle Streamwise Mean Velocity

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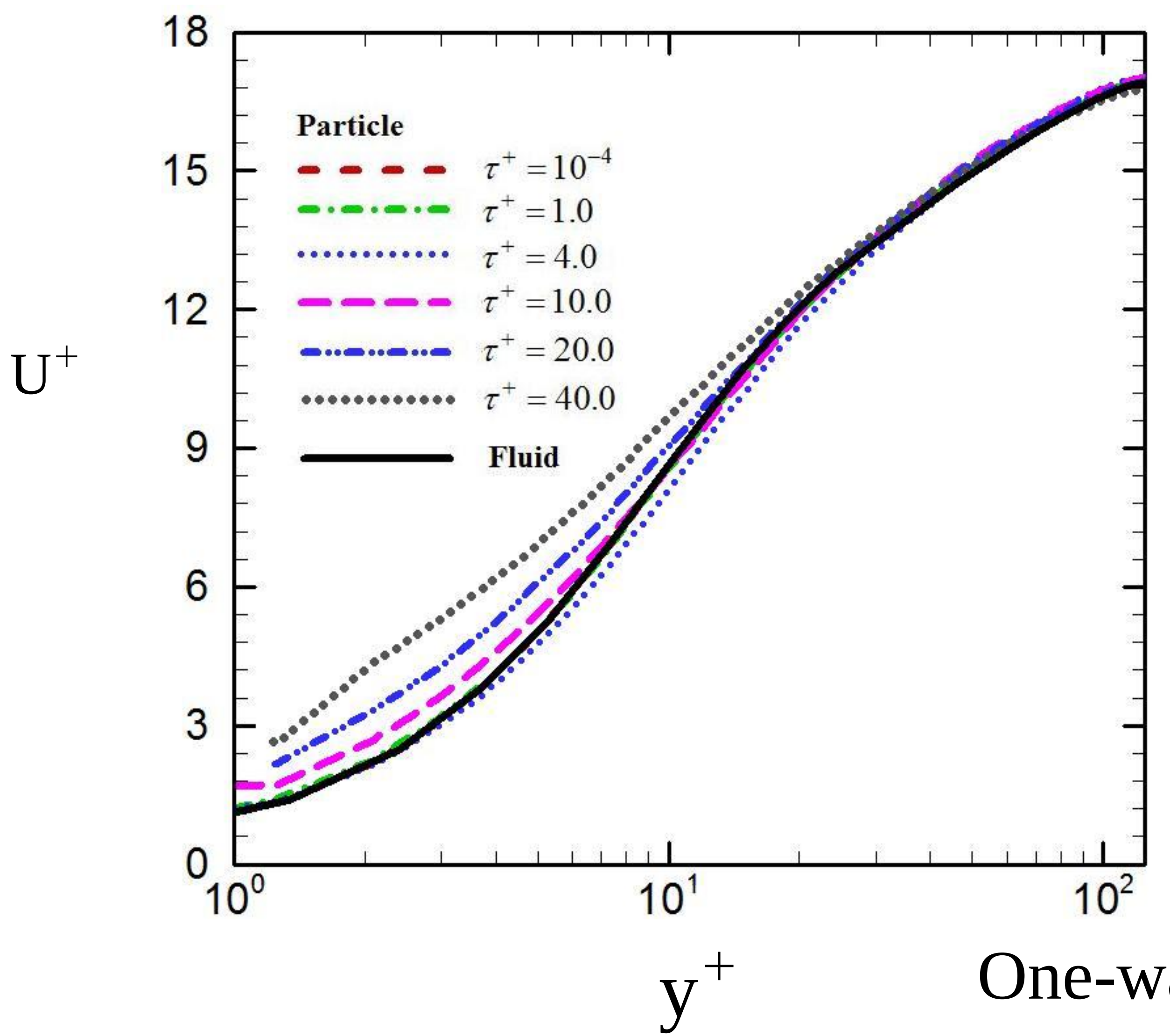

One-way coupling

Fluid and Particle Streamwise Fluctuating Velocities

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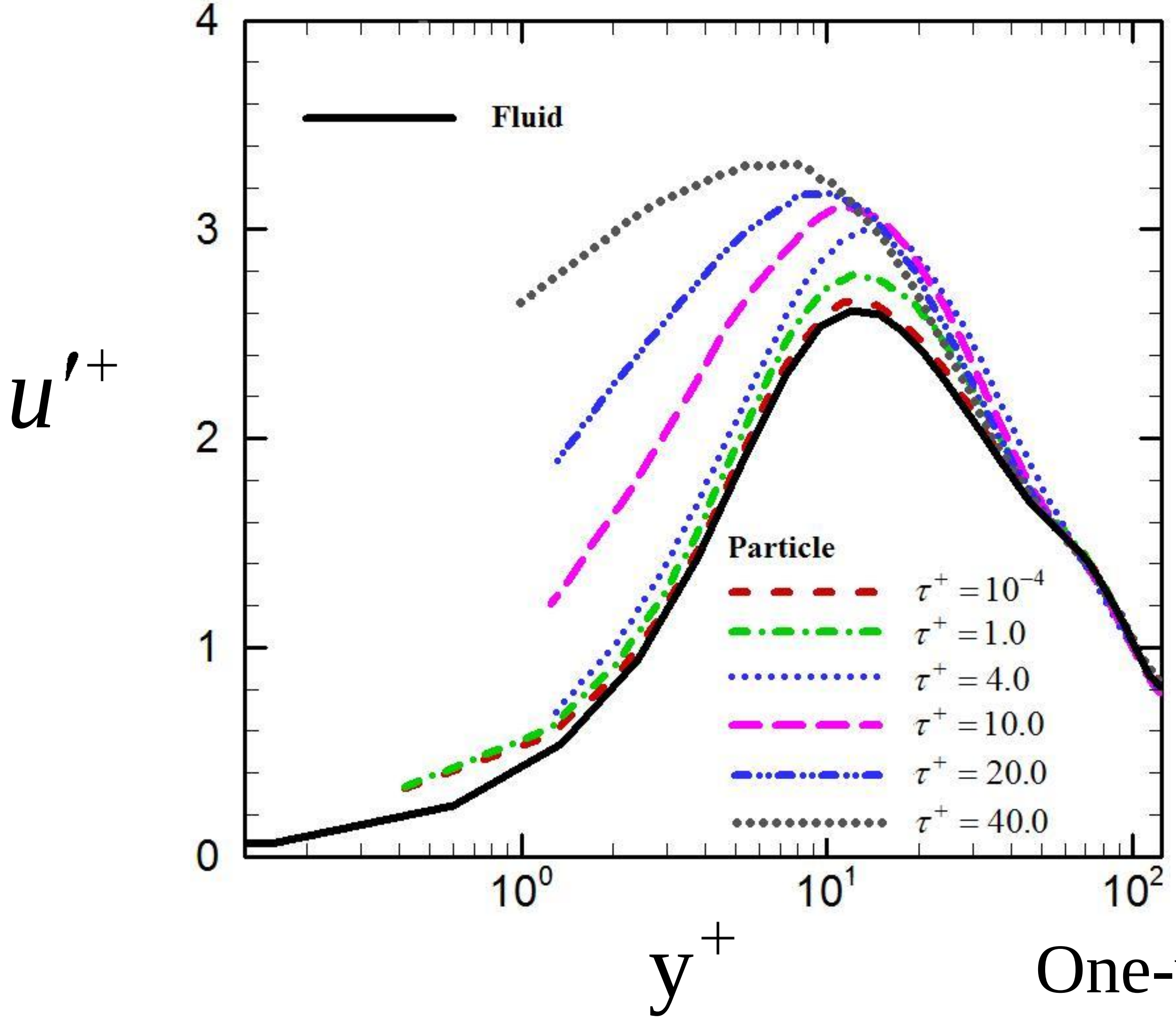
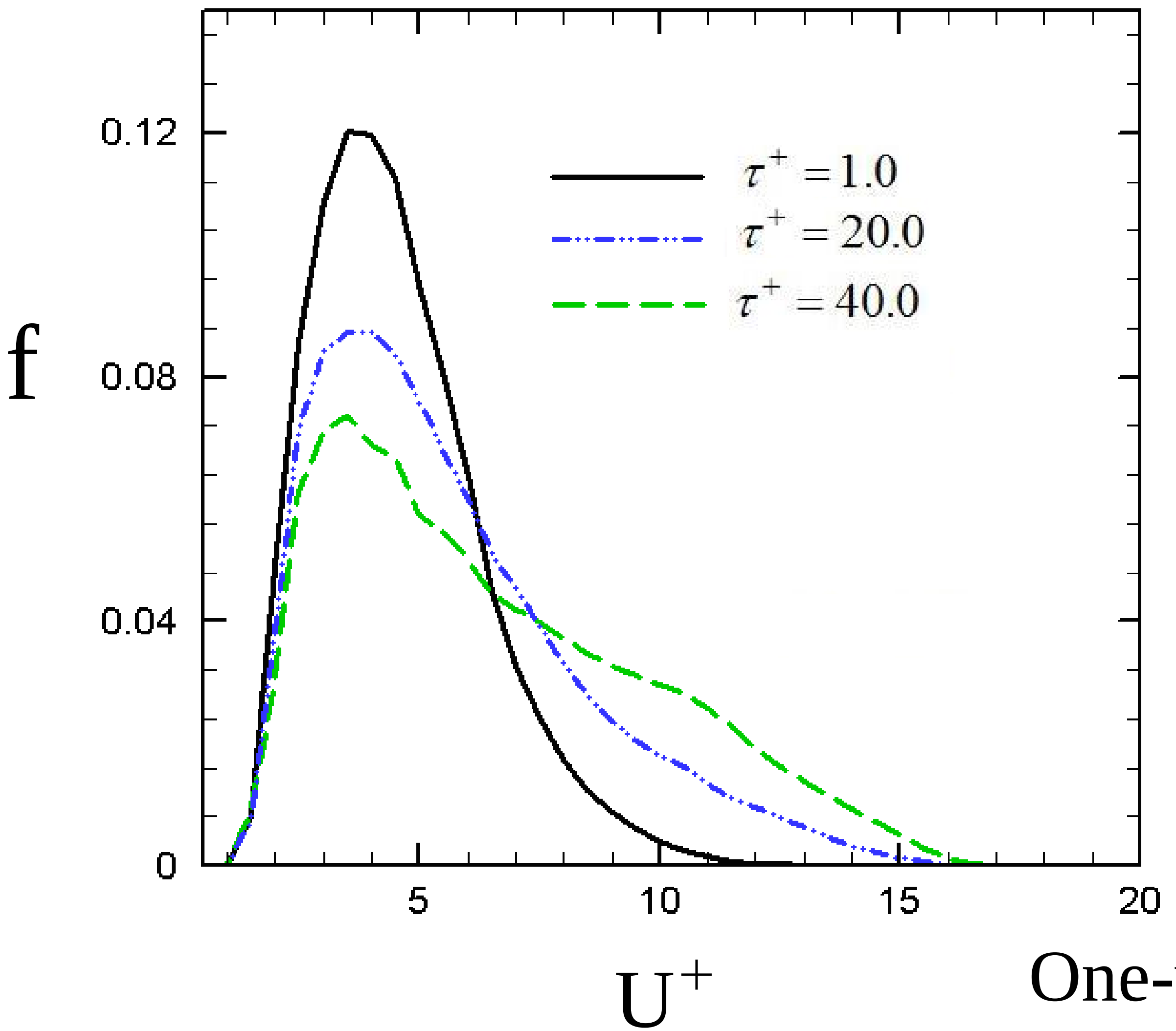


One-way coupling

Velocity Distribution of Particles in 5<y+<7



One-way coupling

Fluctuating Velocities

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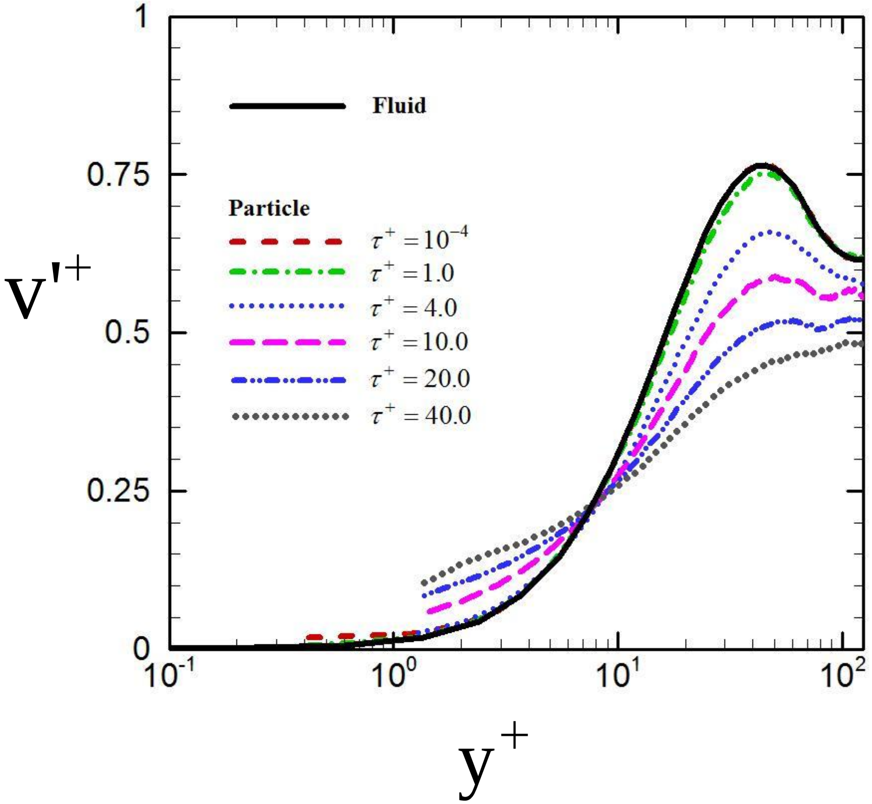
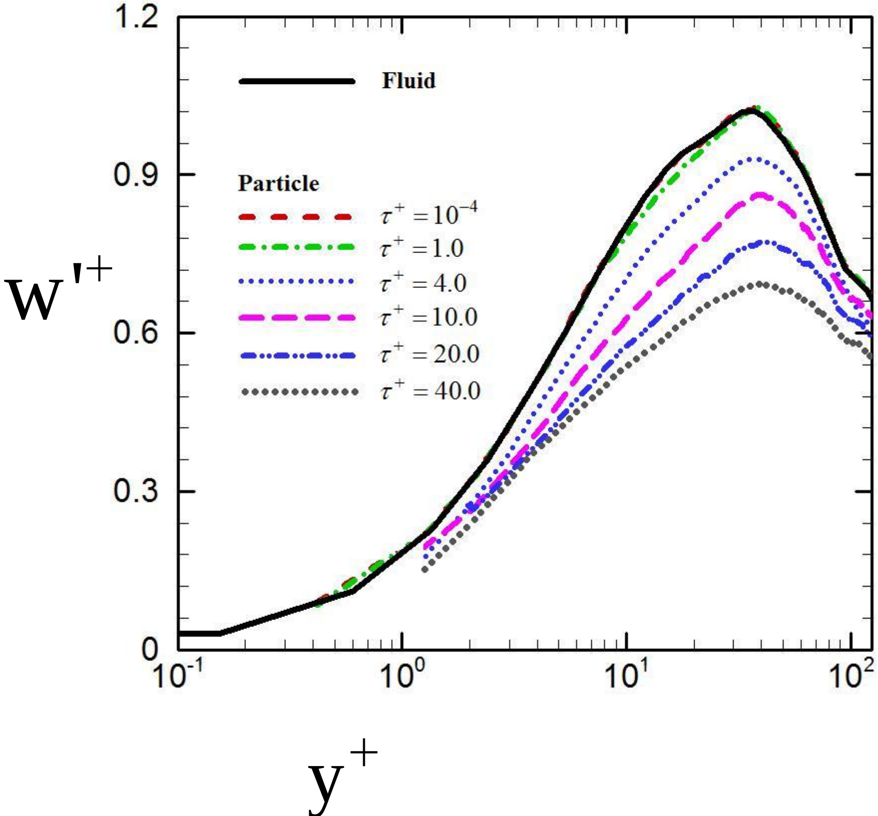
Normal fluctuating velocity



Spanwise fluctuating velocity



One-way coupling

Particle Flux Toward Wall (Turbophoresis)

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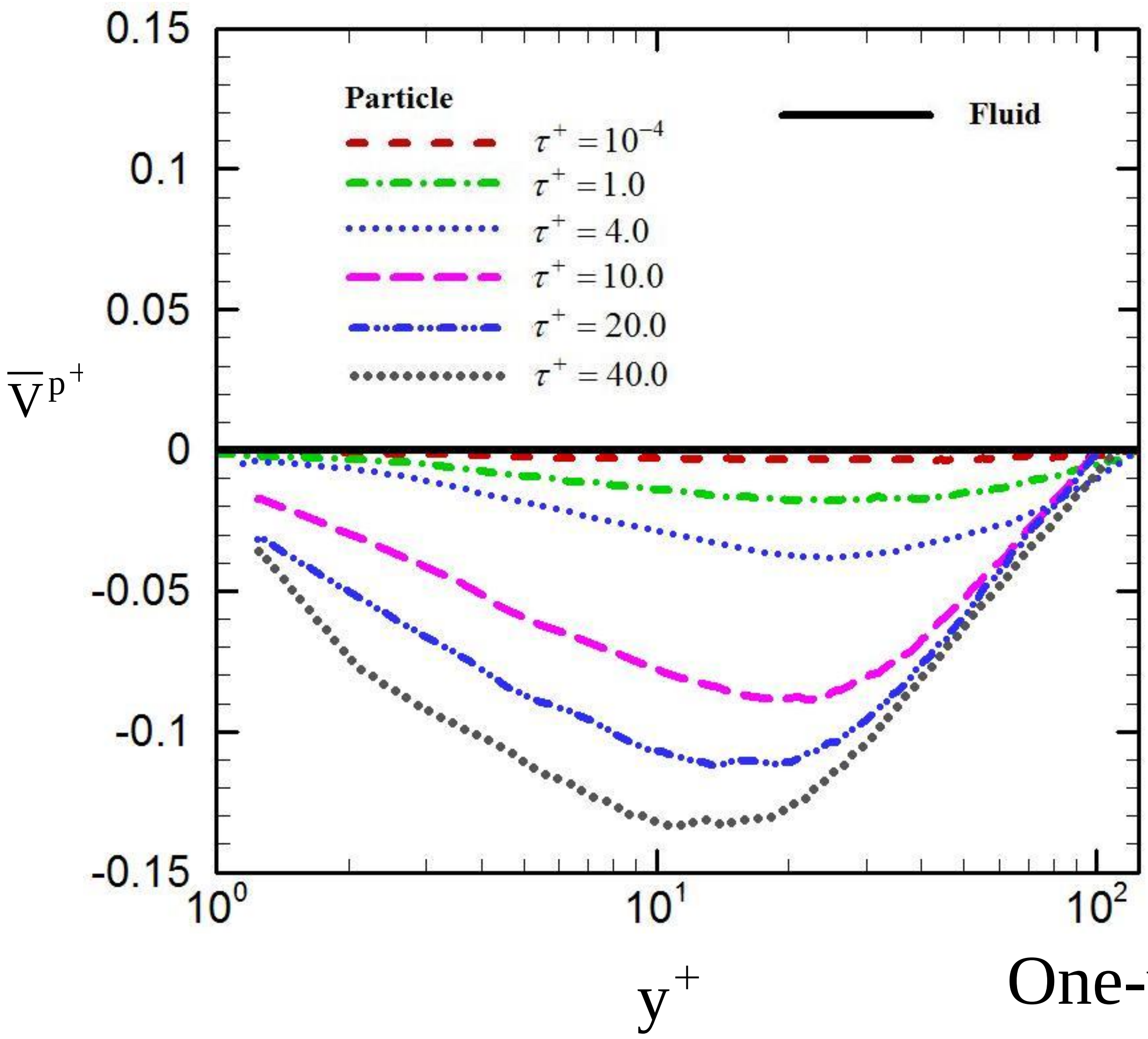

One-way coupling

Sample Velocity Vector Plots

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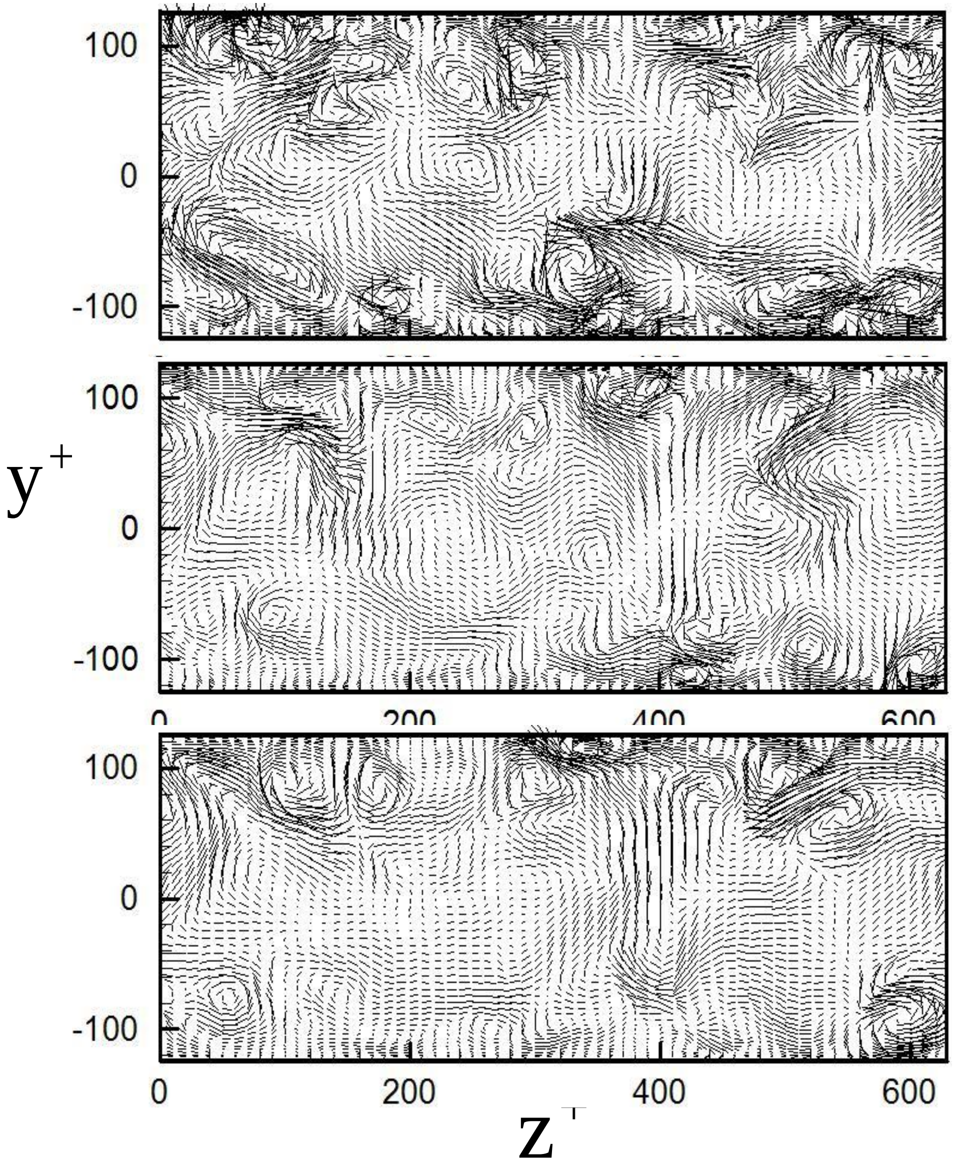

One-way coupling

Four-way coupling, M.L.=20%

Four-way coupling, M.L.=40%

RMS Velocities

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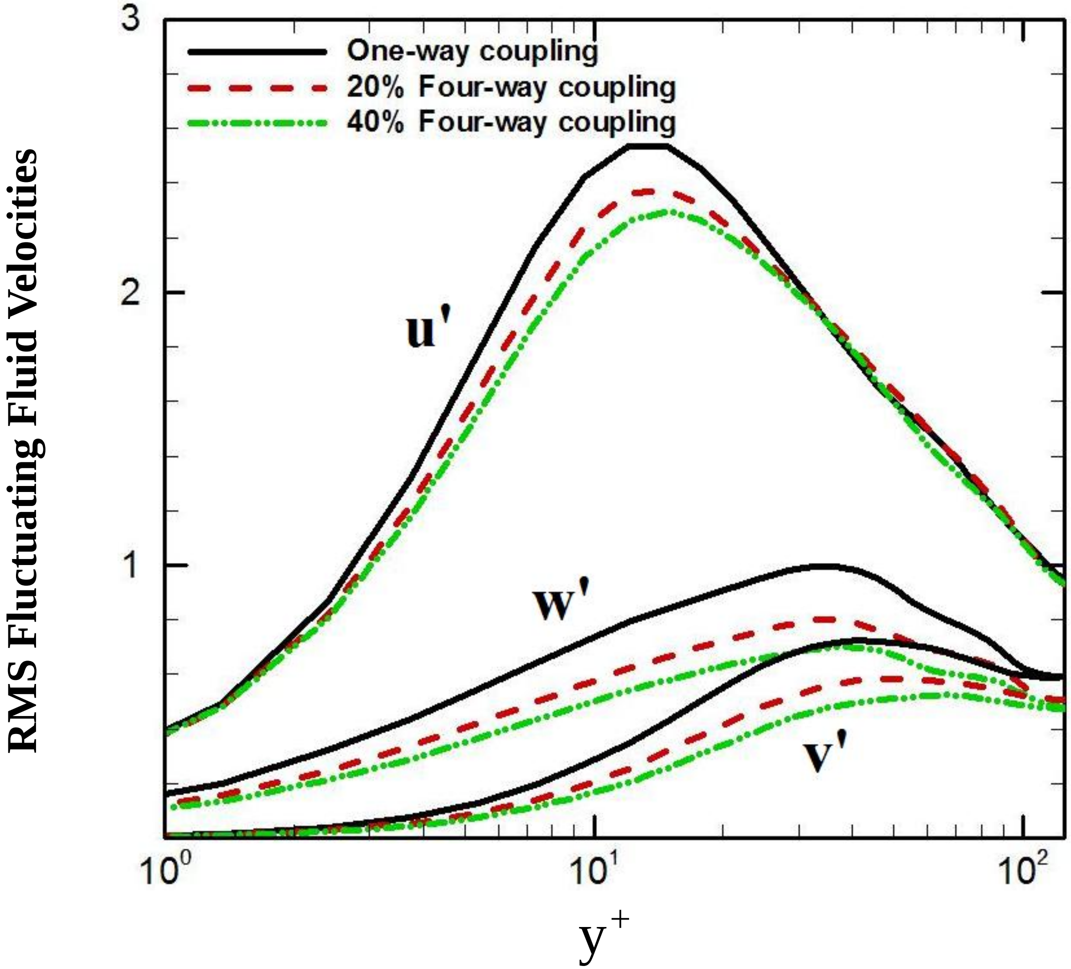

Effects of d=30 micron particles on the flow fluctuating velocities.

Particle Distribution

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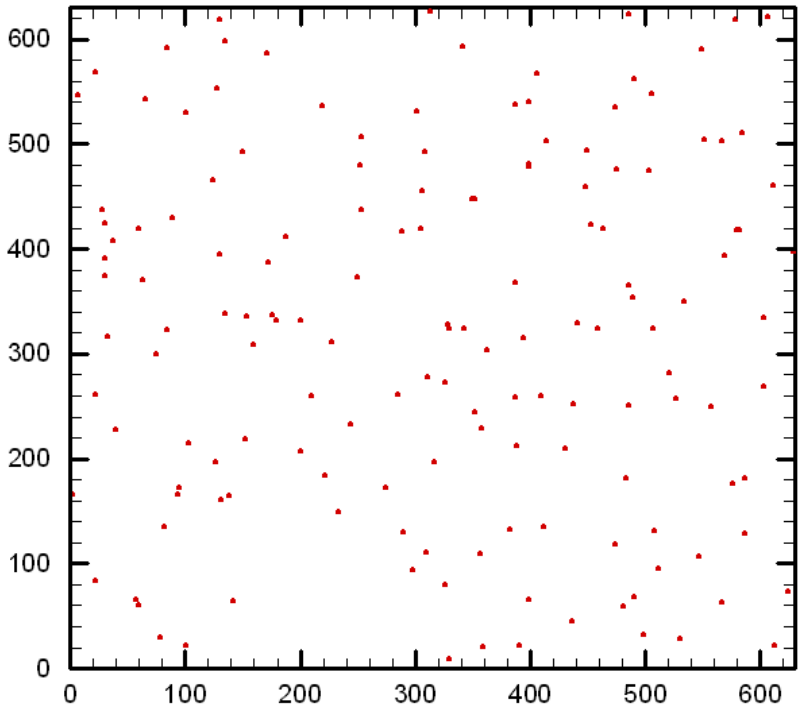
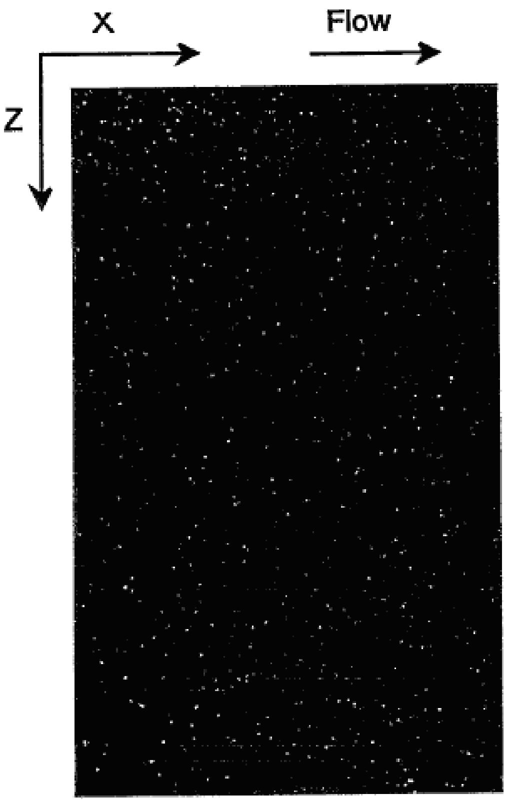


Fessler et al. (1994)



Distribution of 70 micron copper particles (S=7333) at the channel center-plane.

Particle Distribution

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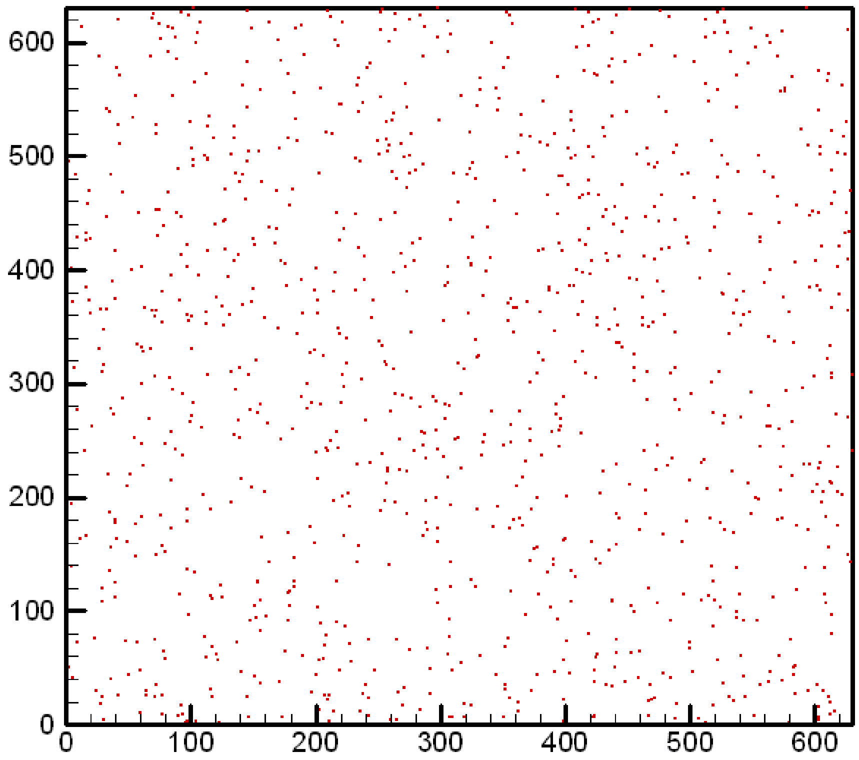
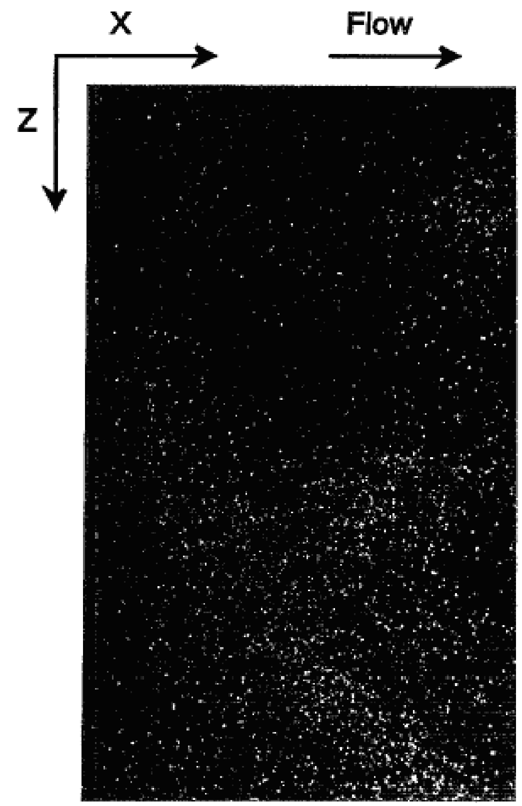


Fessler et al. (1994)



Distribution of 50 micron glass particles (S=2030) at the channel center-plane

Particle Distribution

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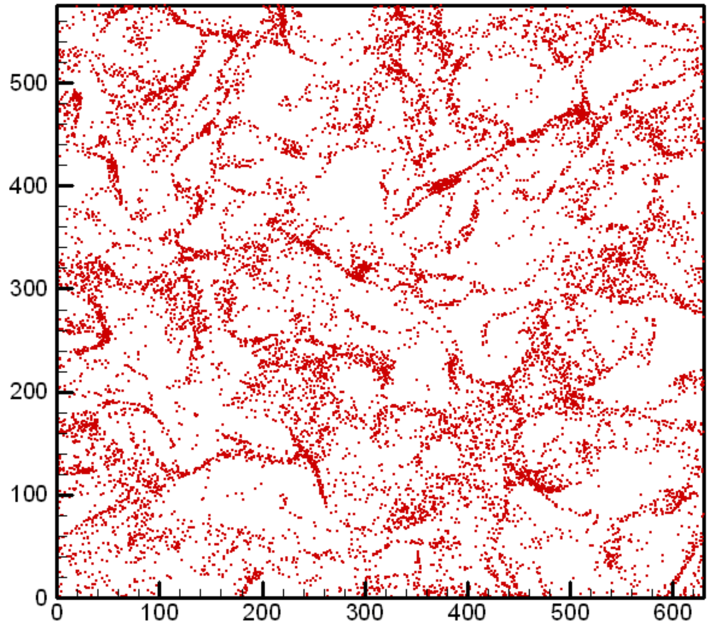
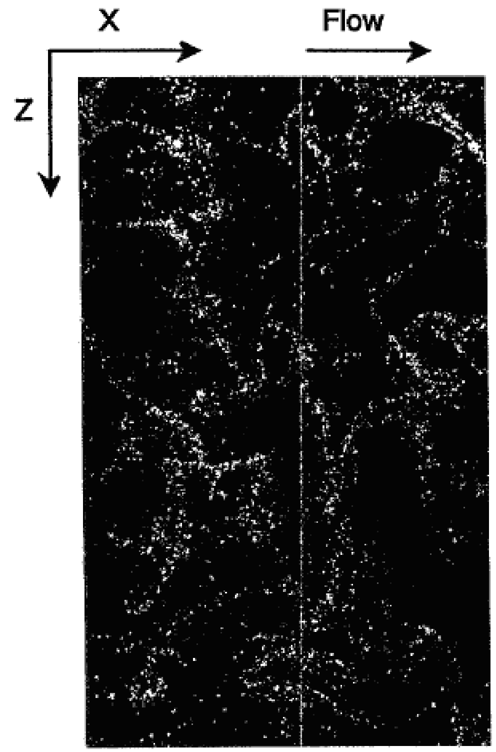


Fessler et al. (1994)



Distribution of 28 micron Lycopodium particles (S=826) at the channel center-plane

Particle Distribution

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The lack of preferential concentration for copper and glass particles could be due to

- **Particle High Stokes number**
- **Inter-particle collisions**

Particle Distribution at the channel center-plane

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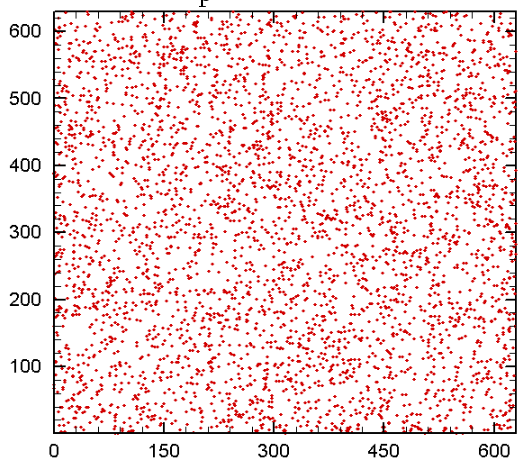
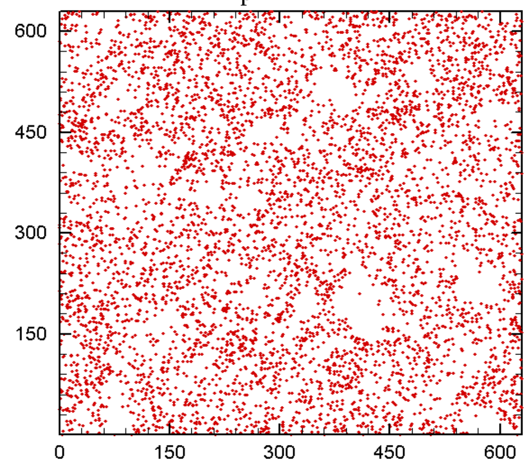
One Way Coupling

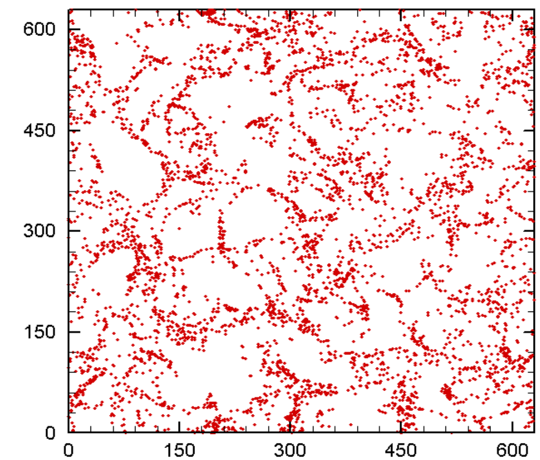
$\tau_p^{\ +} = 10^{-4}$



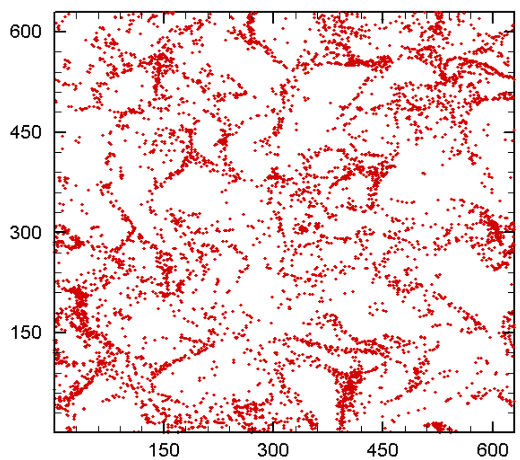
$\tau_p^{\ +} = 1.0$



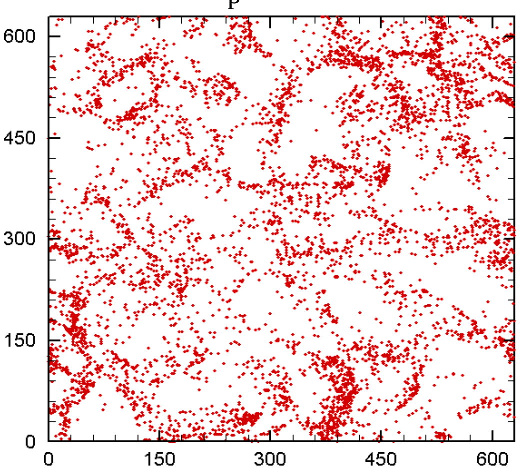
$\tau_p^{\ +} = 4.4$



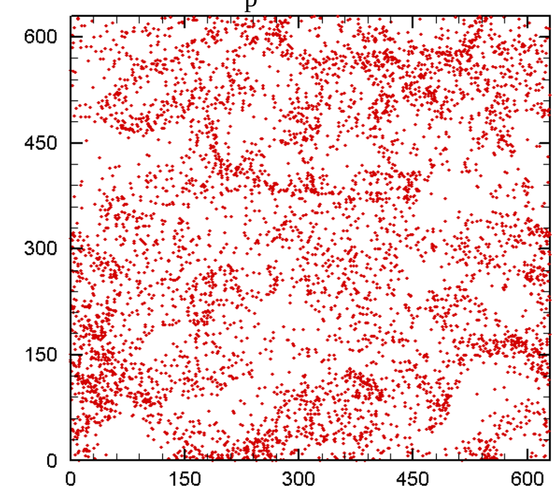
$\tau_p^{\ +} = 10.0$



$\tau_p^{\ +} = 20$



$\tau_p^{\ +} = 40.0$



Particle Distribution and Vorticity Contours

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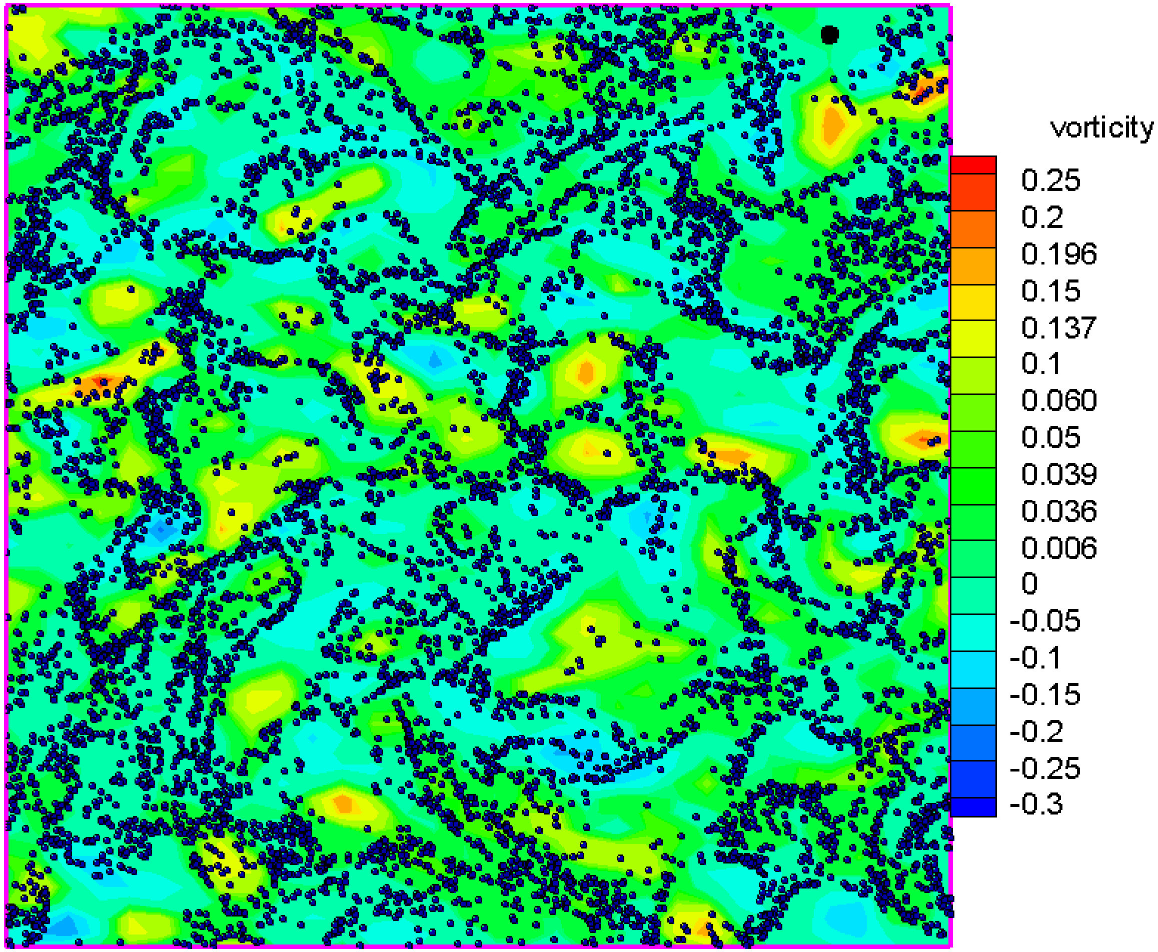
$$\tau_p^{\,+} = 10.0$$

Channel Center Plane



Particle Distribution at the channel center-plane

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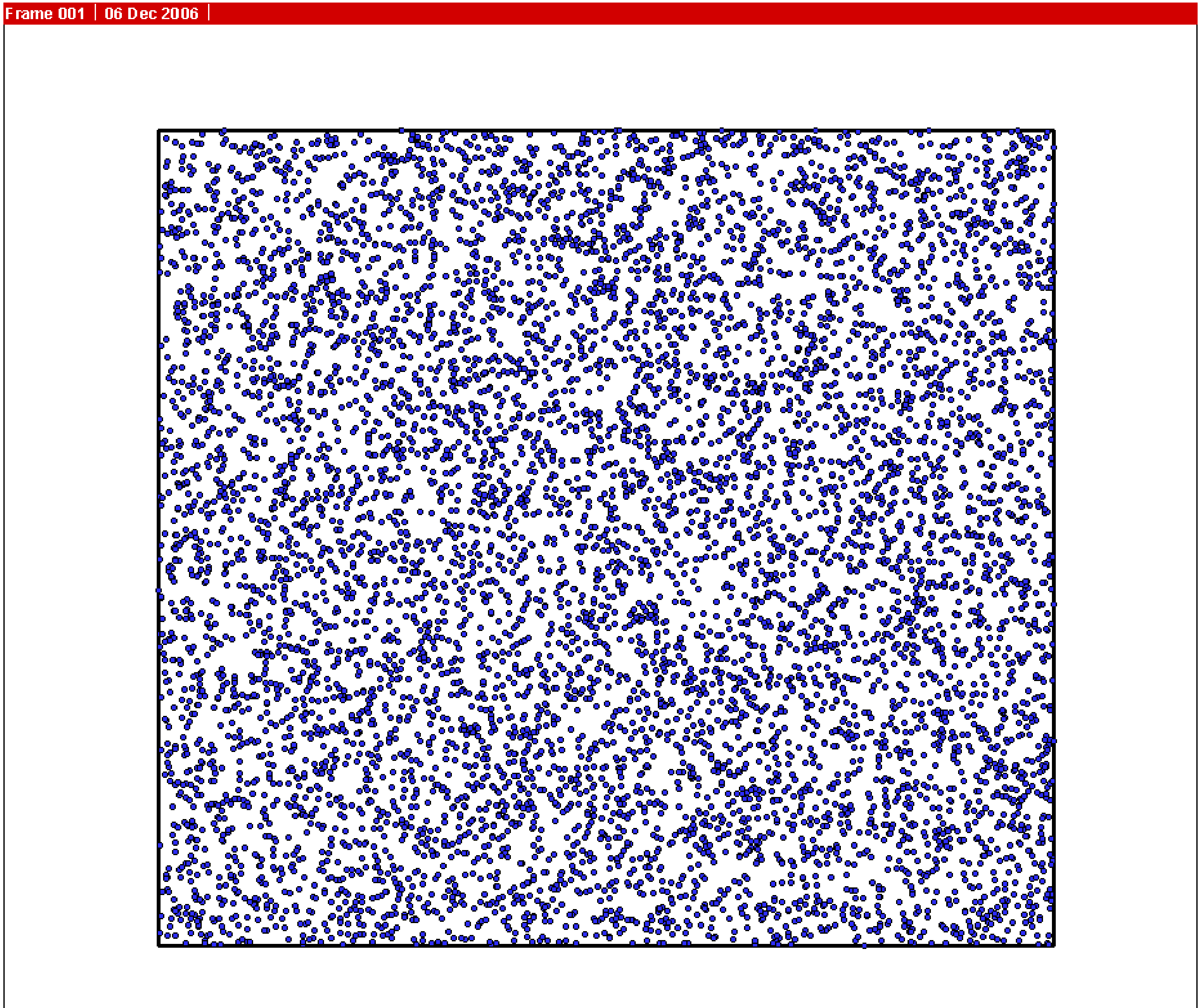
$\tau_p^{\,+} = 10.0$



Particle Distribution in the Wall Region

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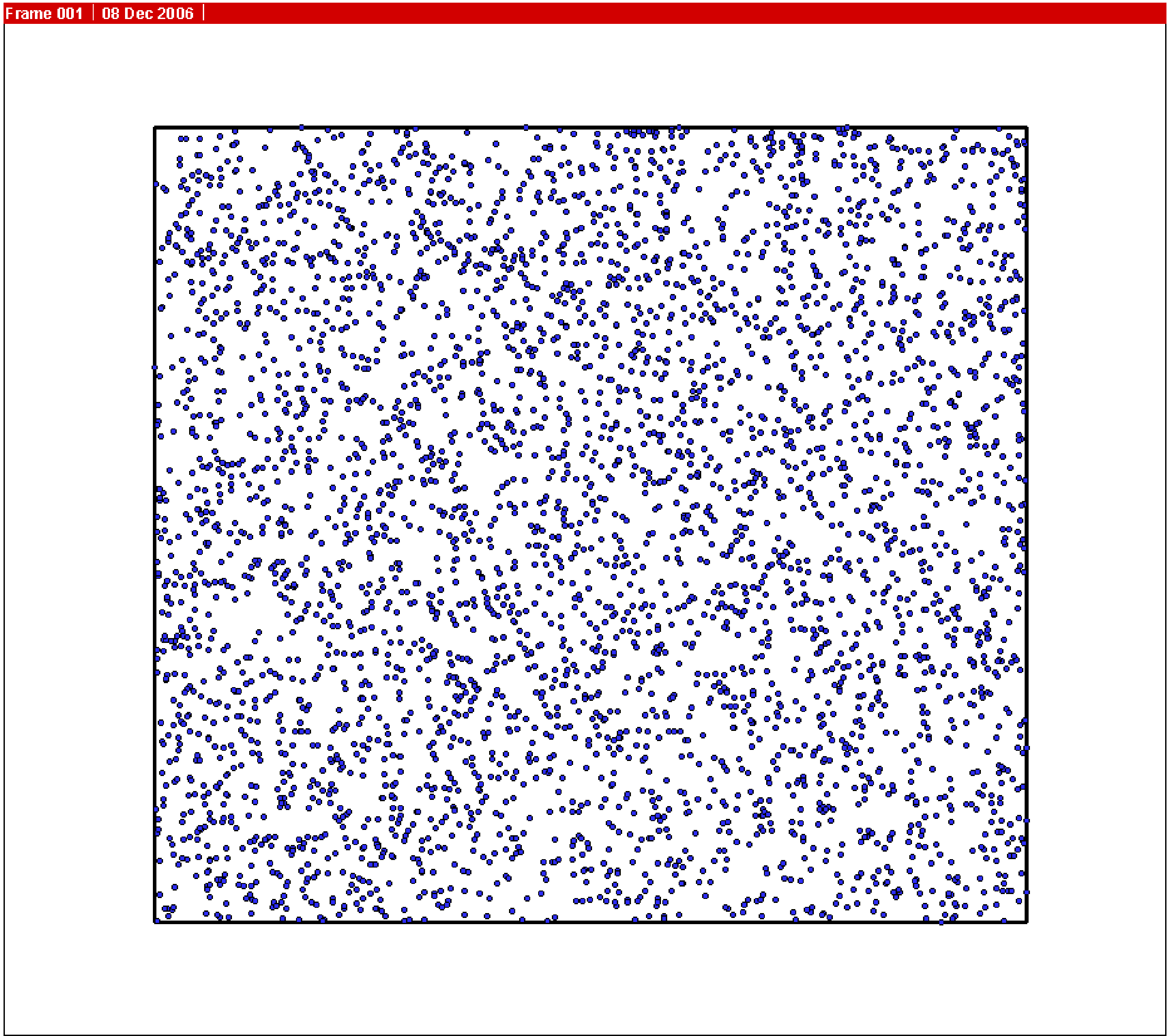
$\tau_p^+ = 10.0$



Particle Concentration Profiles

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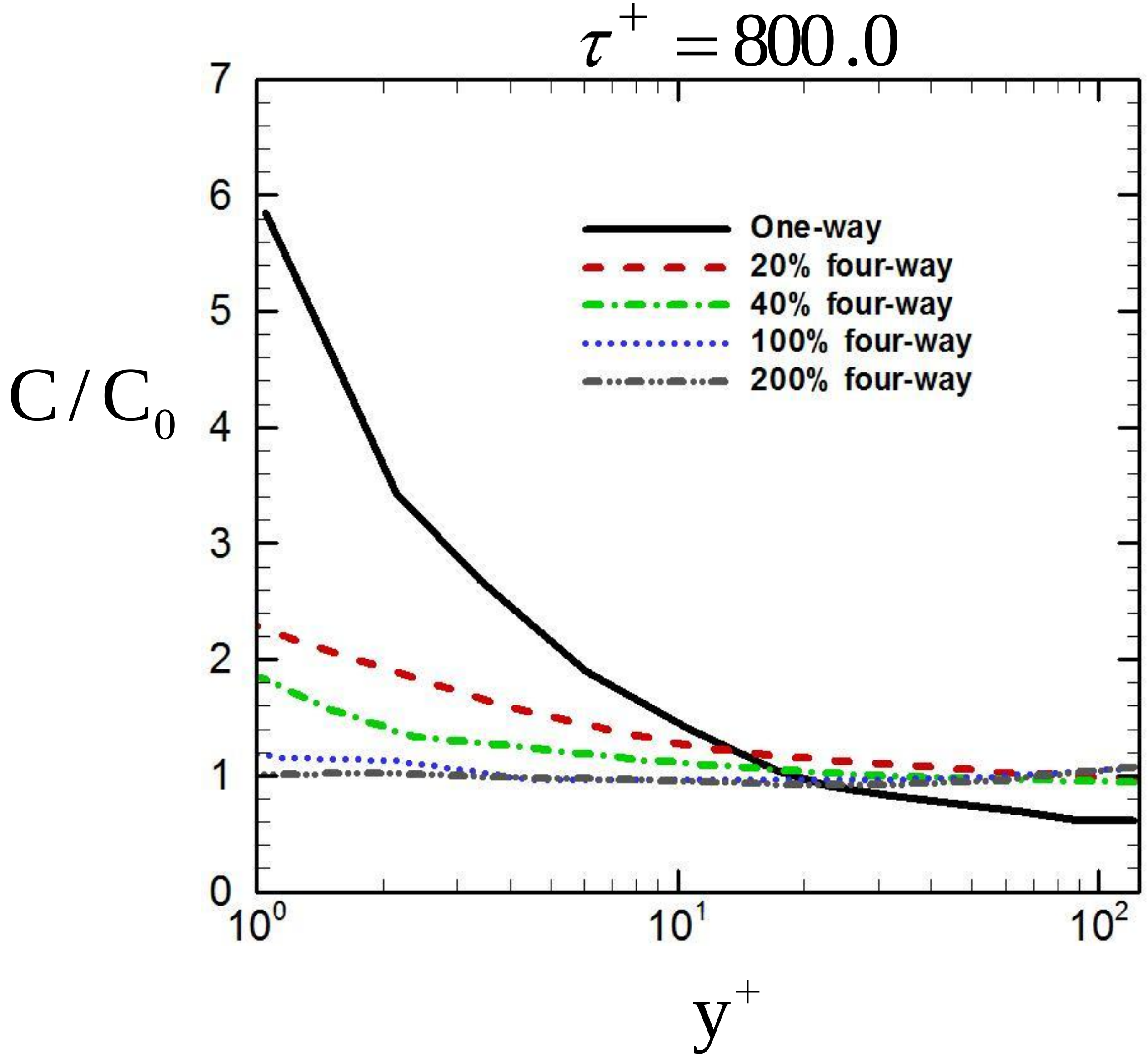

Particle Distribution at the channel center-plane

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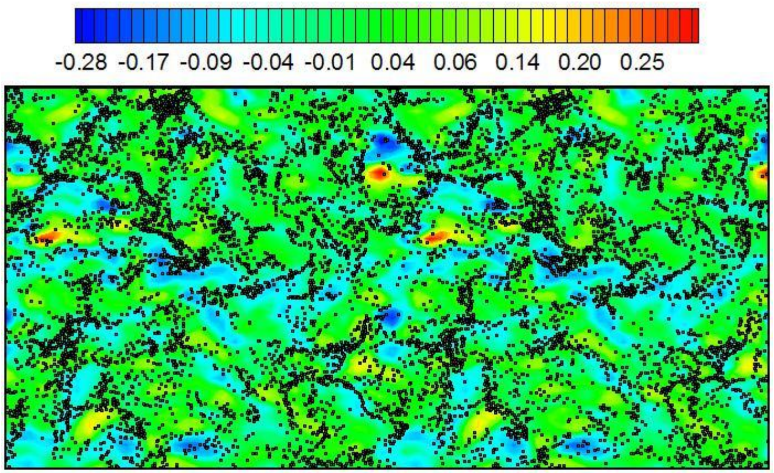
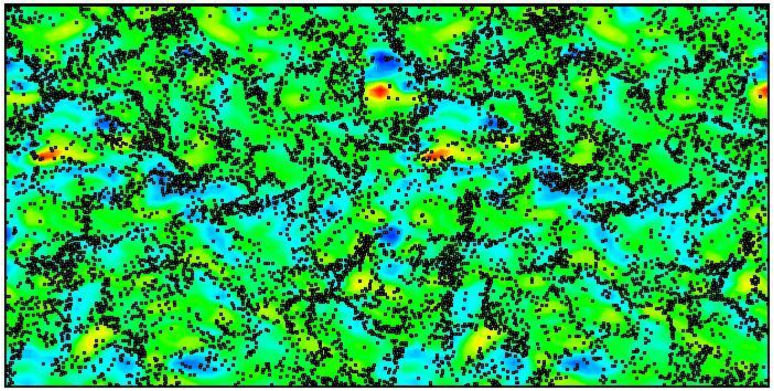
$\tau^{+} = 20.0$ $\quad$ M.L. $= 40\%$

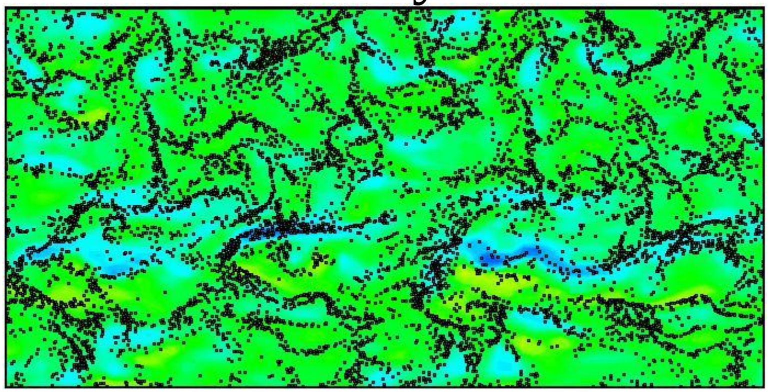
One-way



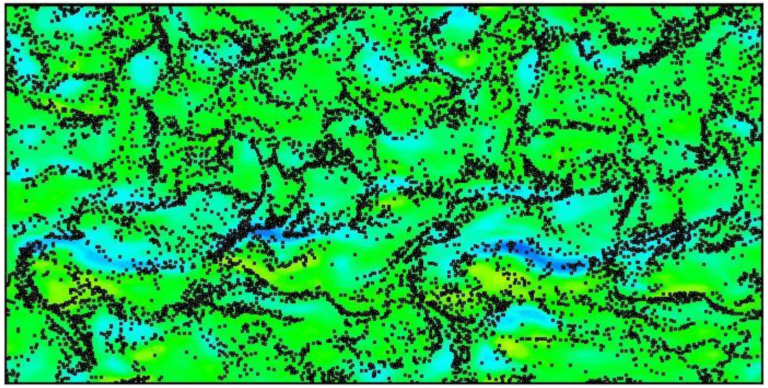
Collisions only



Two-way



Four-way



Particle Distribution in the Wall Region

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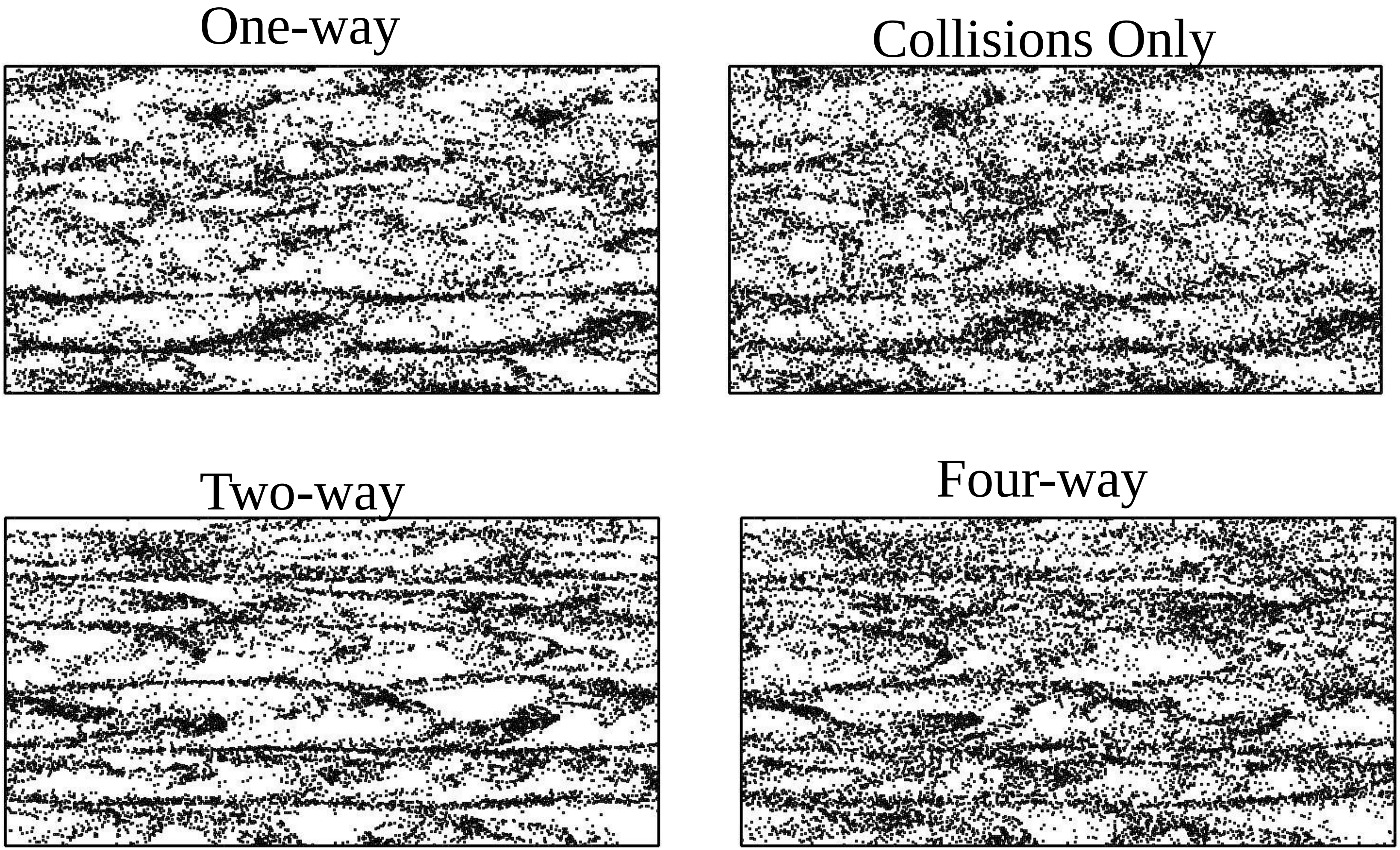
$\tau^{+} = 20.0$ M.L. $= 40\%$ $y^{+} = 10$



Numerber of Deposited Particles Versus Time

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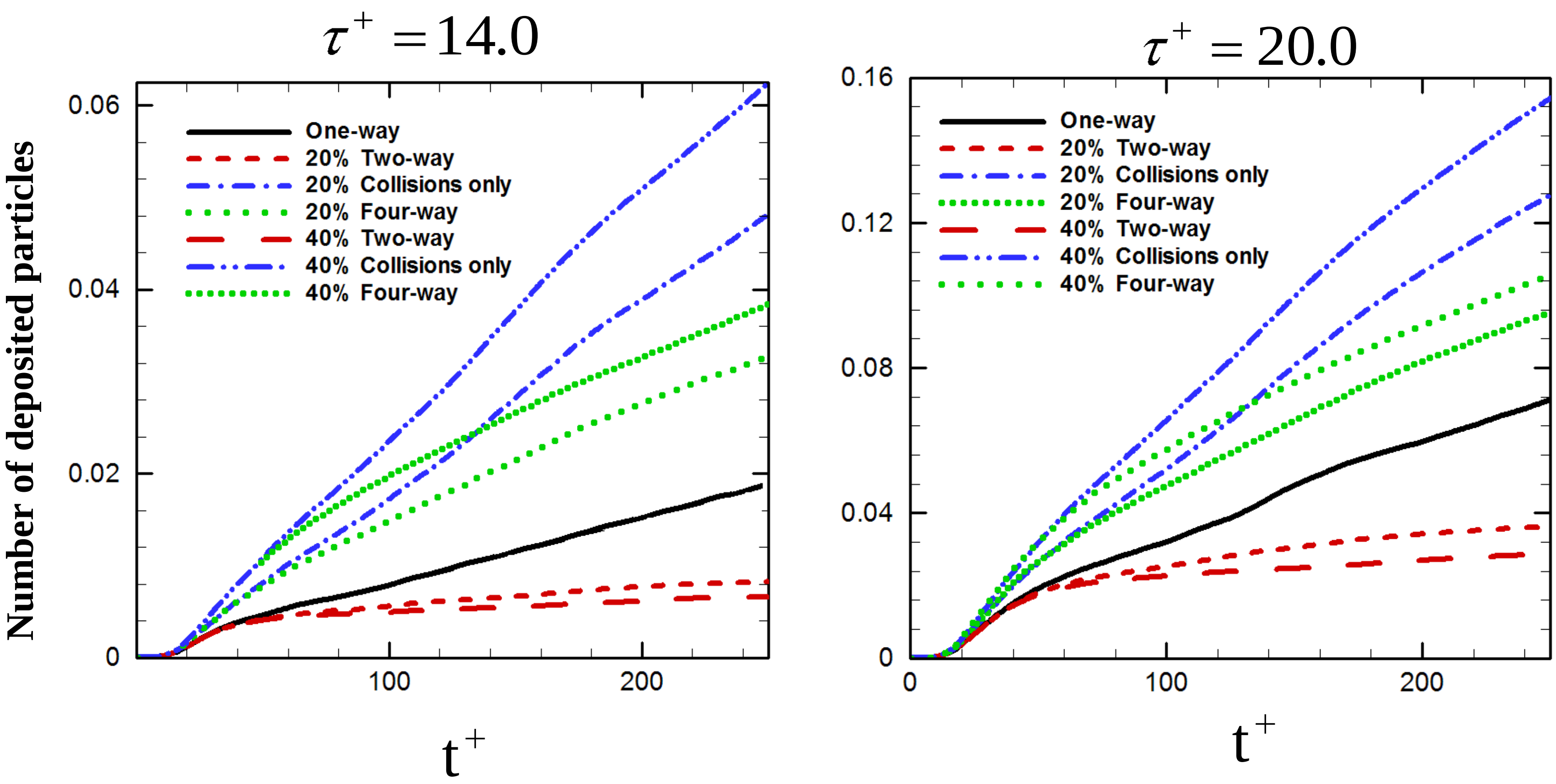

Particle Deposition Velocity

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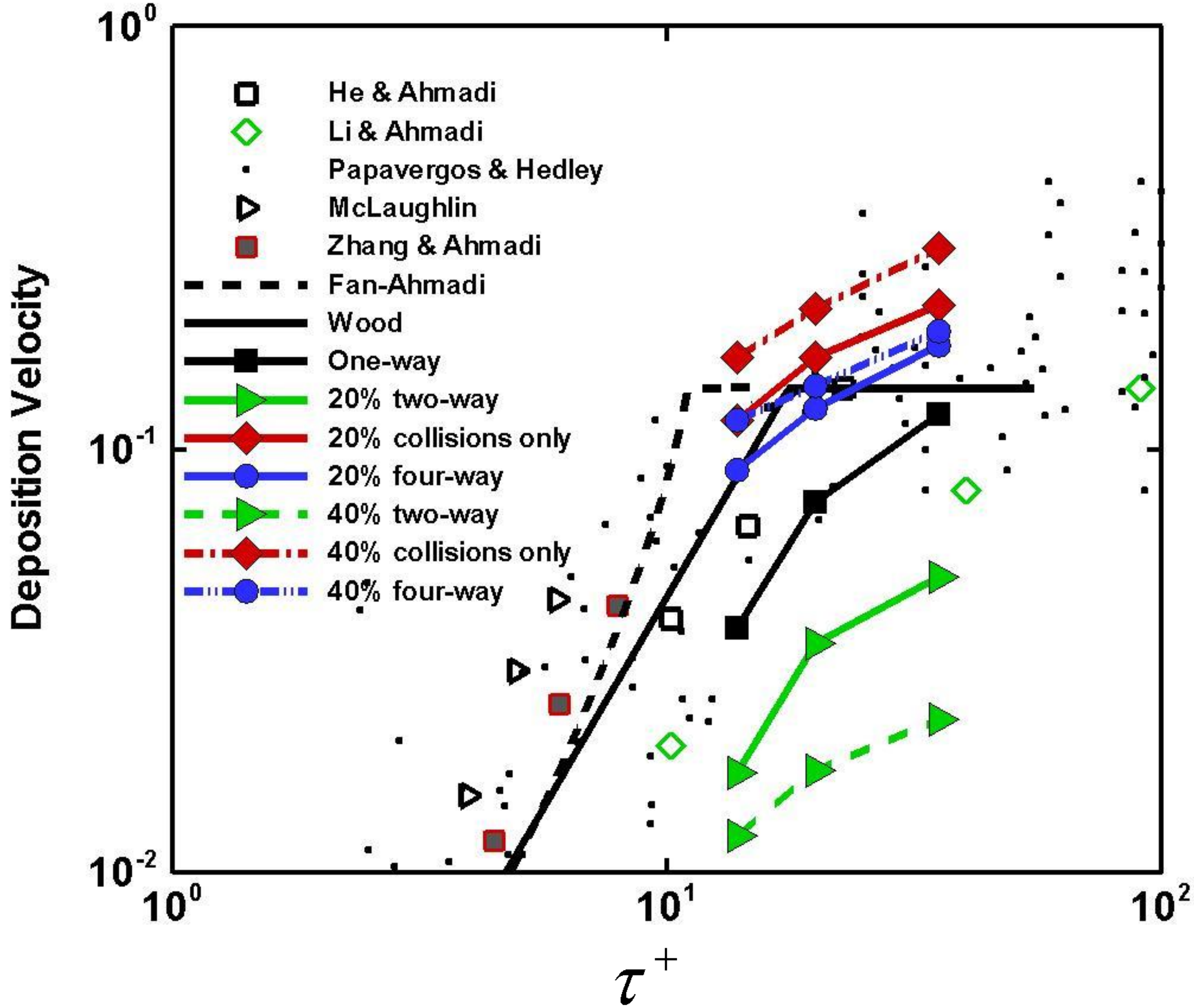

Particle Normal Fluctuating Velocity

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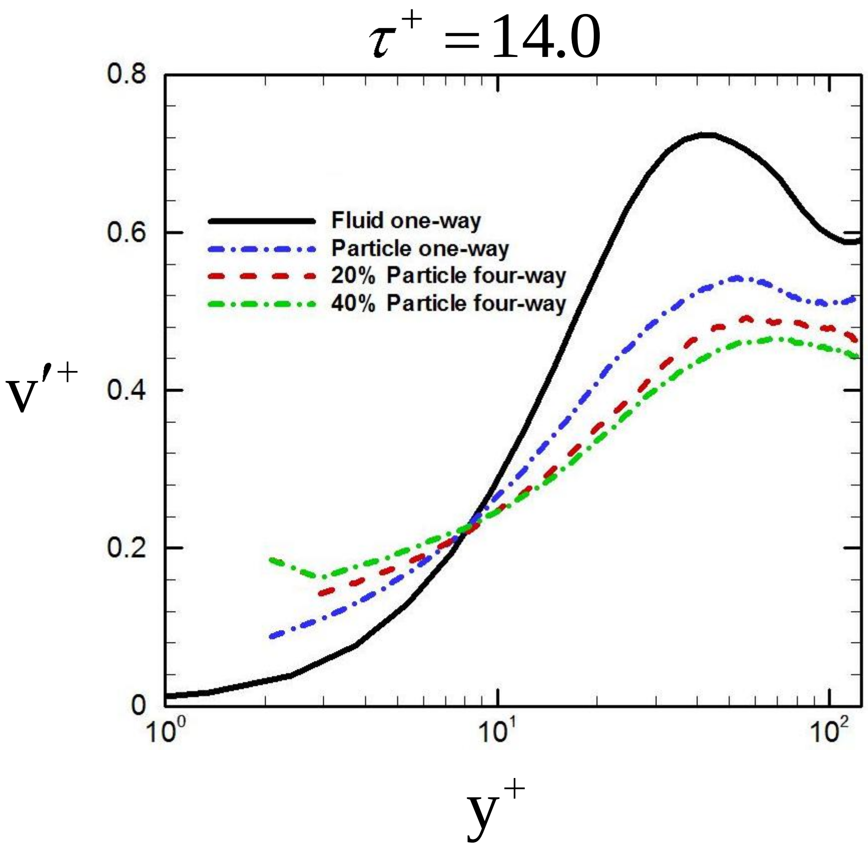

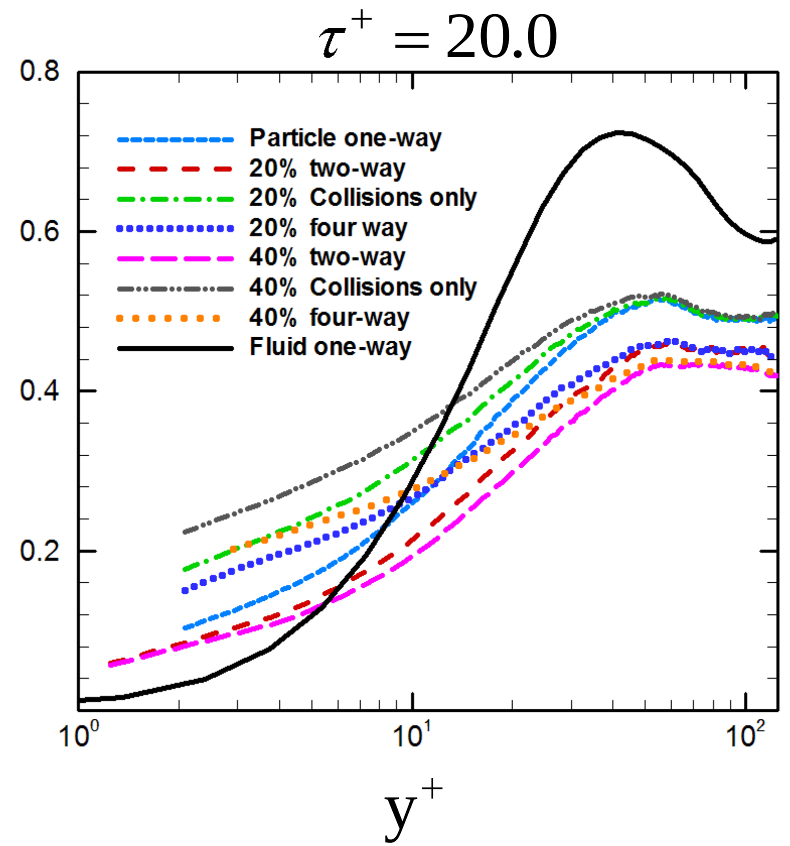

Particle Spanwise Fluctuating Velocity

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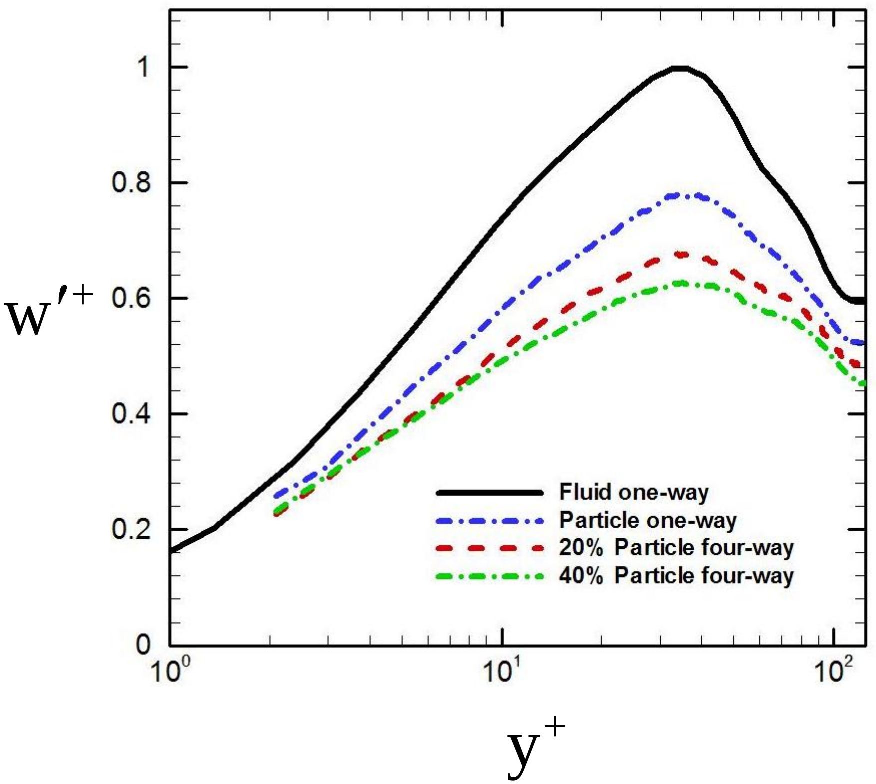
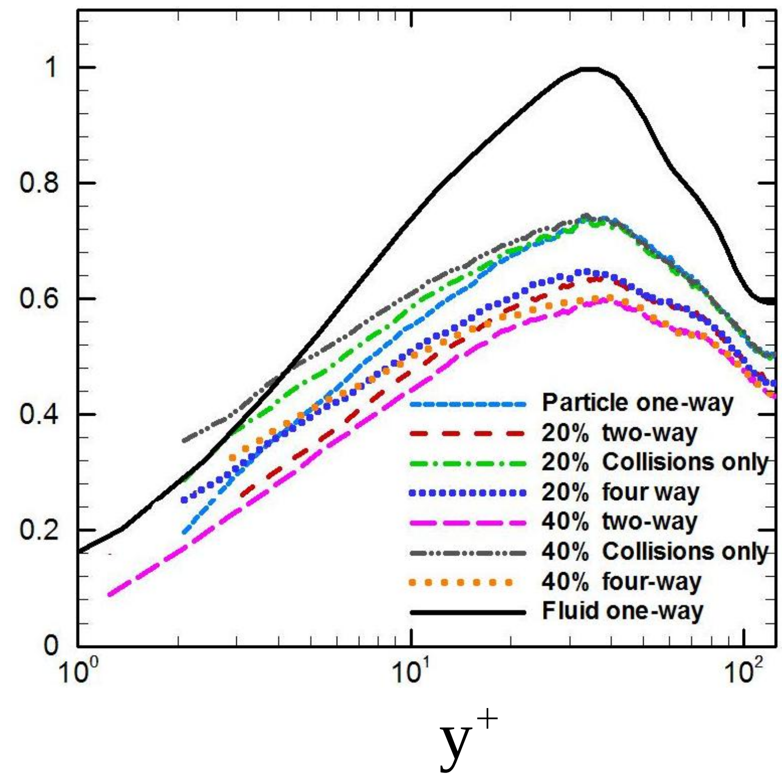
$\tau^+ = 14.0$



$\tau^+ = 20.0$



Particle Streamwise Fluctuating Velocity

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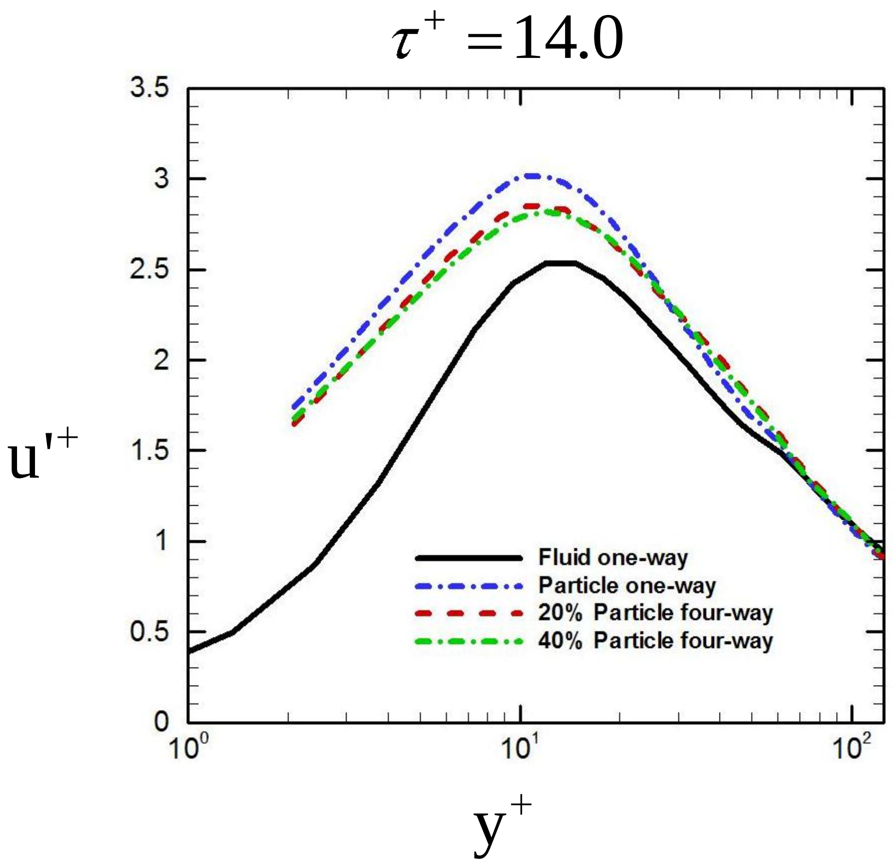

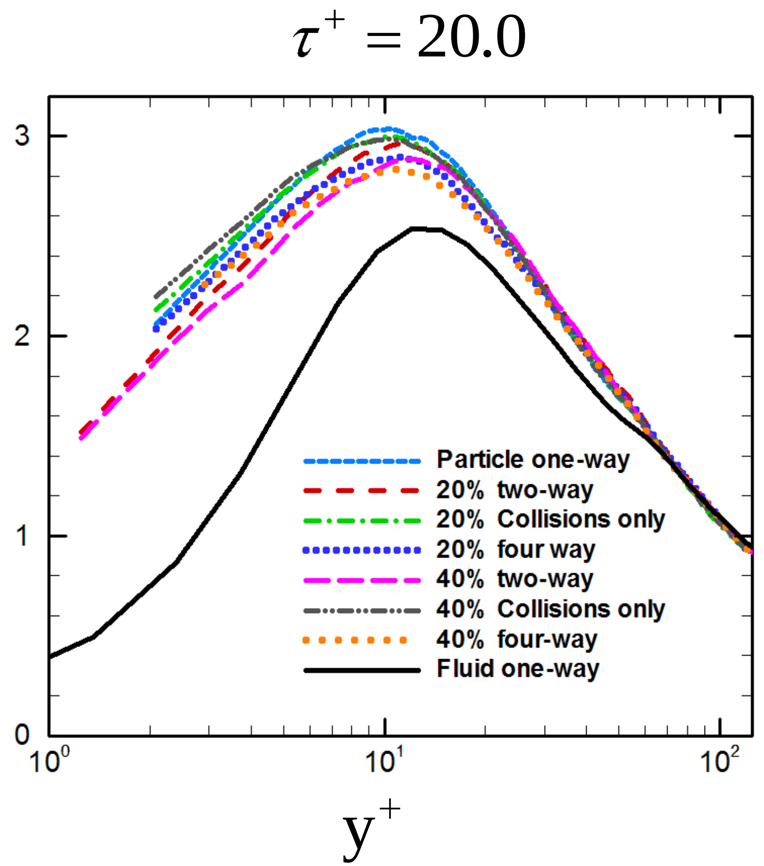

Particle Concentration Profiles

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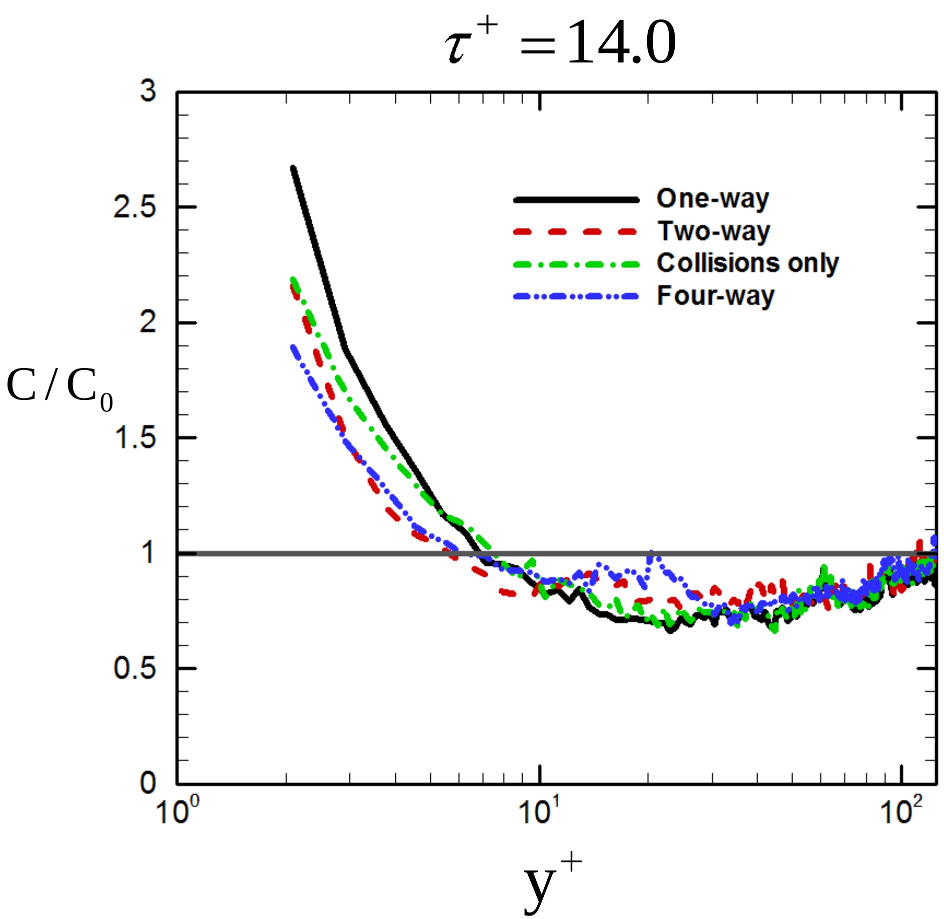
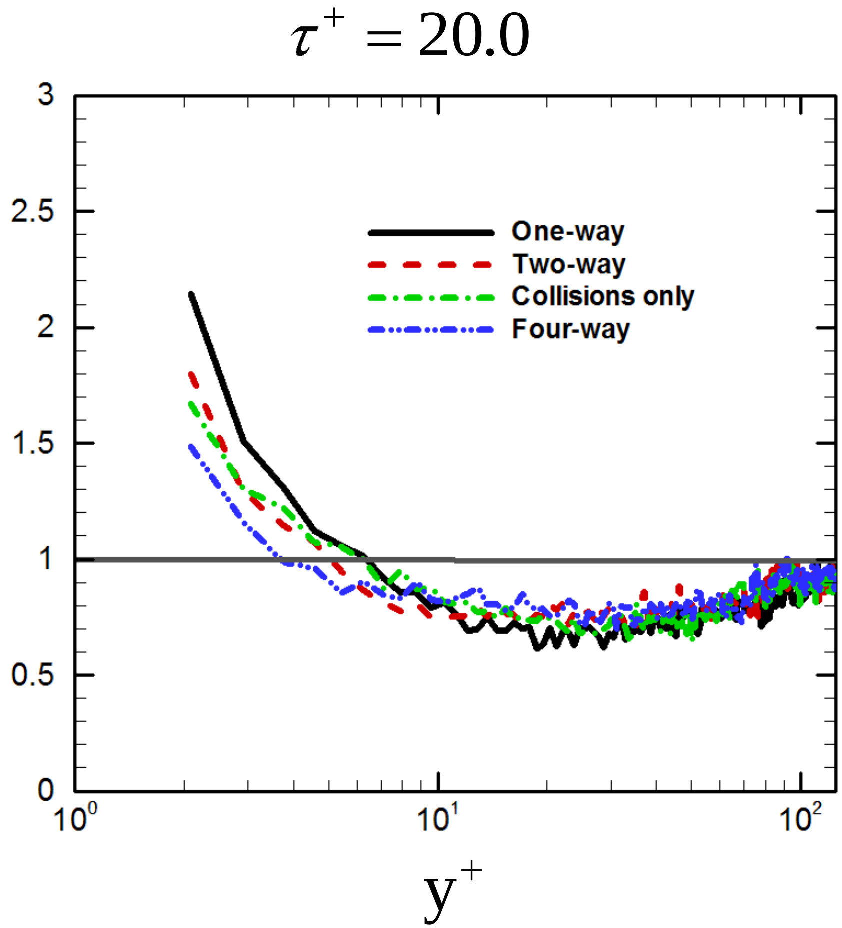
Mass Loading = 20%





Particle Concentration Profiles

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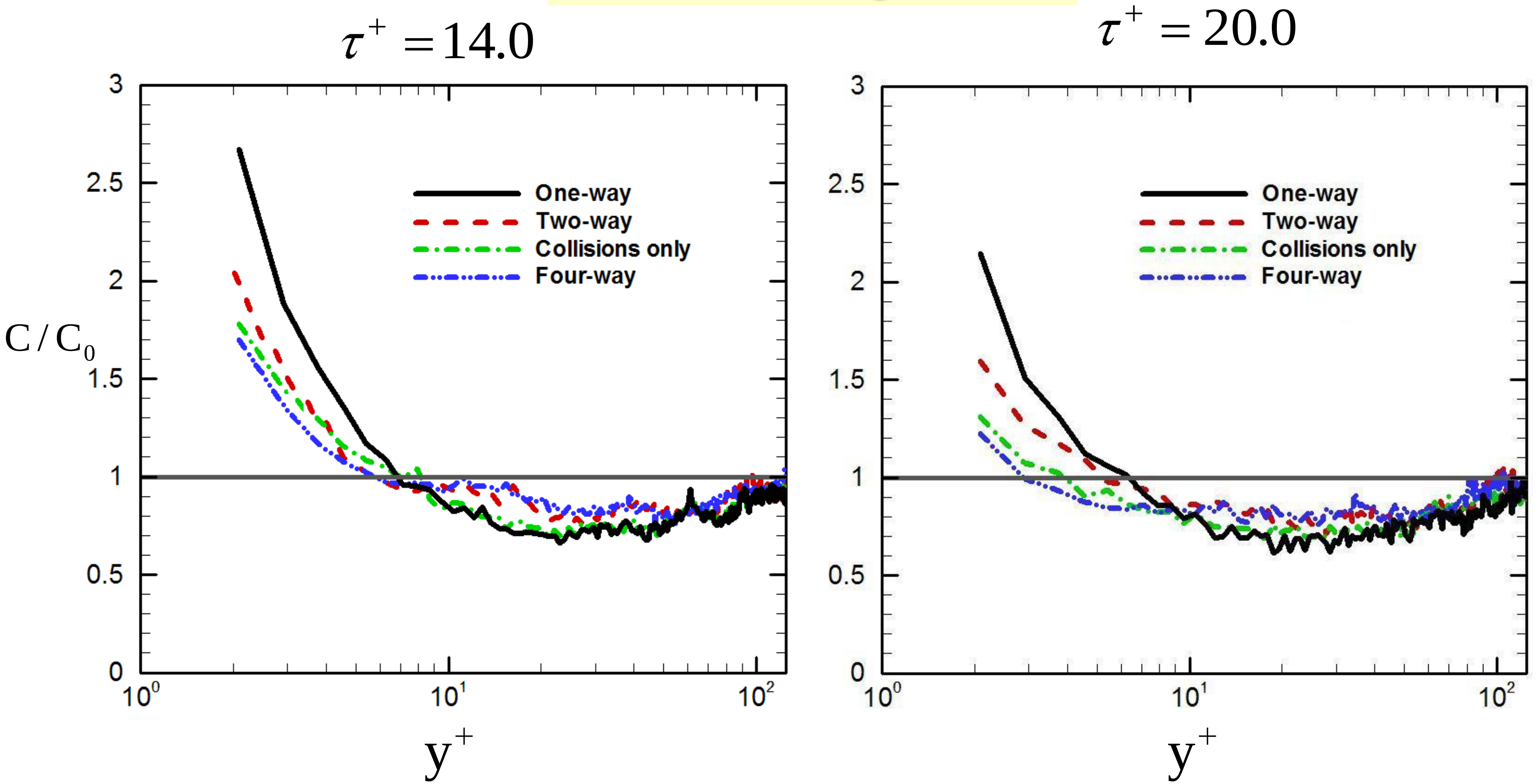
Mass Loading = 40%



Comparisons with Model

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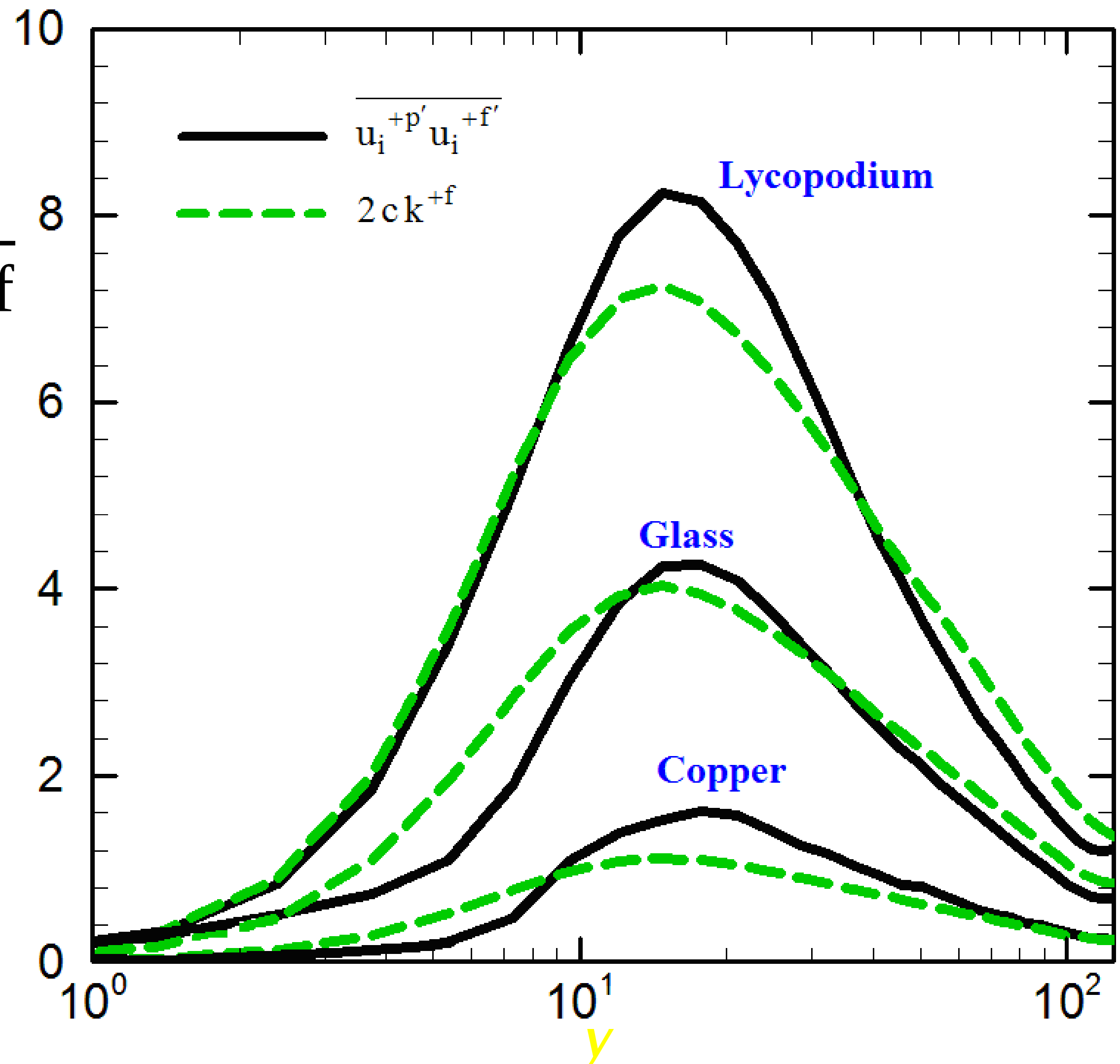
$$\overline{u_i^{+p'} u_i^{+f}}$$

$$2ck^{+f}$$



Conclusions

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- Turbulence coherent vortical near-wall structure plays an important role on the particle deposition concentration profiles.
- Presence of particles attenuates the intensity of the fluid fluctuations, and as particle mass loading increases, the level of attenuation increases.
- Inter-particle collisions increases the particle deposition velocity while two-way coupling decreases it.
- Inter-particle collisions and two-way coupling reduce the particle accumulation near the wall.

Thank You!

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Questions?