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DNS of Particles and Fibers Transport and Deposition in Duct Flows

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Outline

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- Literature Review
- Particles
  - Governing Equations
  - Results
- Fibers
  - Governing Equations
  - Results
- Concluding Remarks

Flow Regimes

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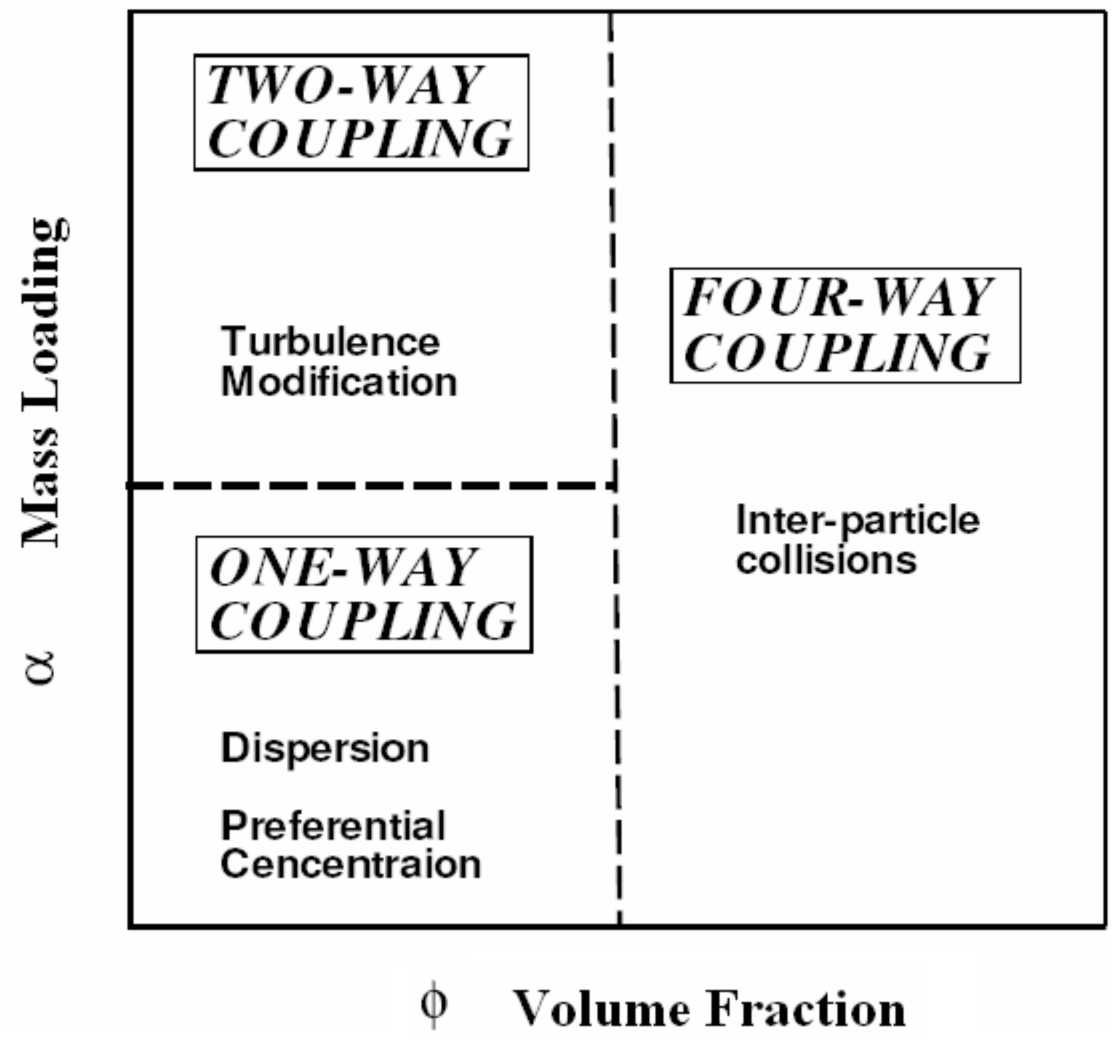

Direct Numerical Simulations

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Wall Units

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

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

Navier-Stokes

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

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

Flow Between Two Parallel Plates

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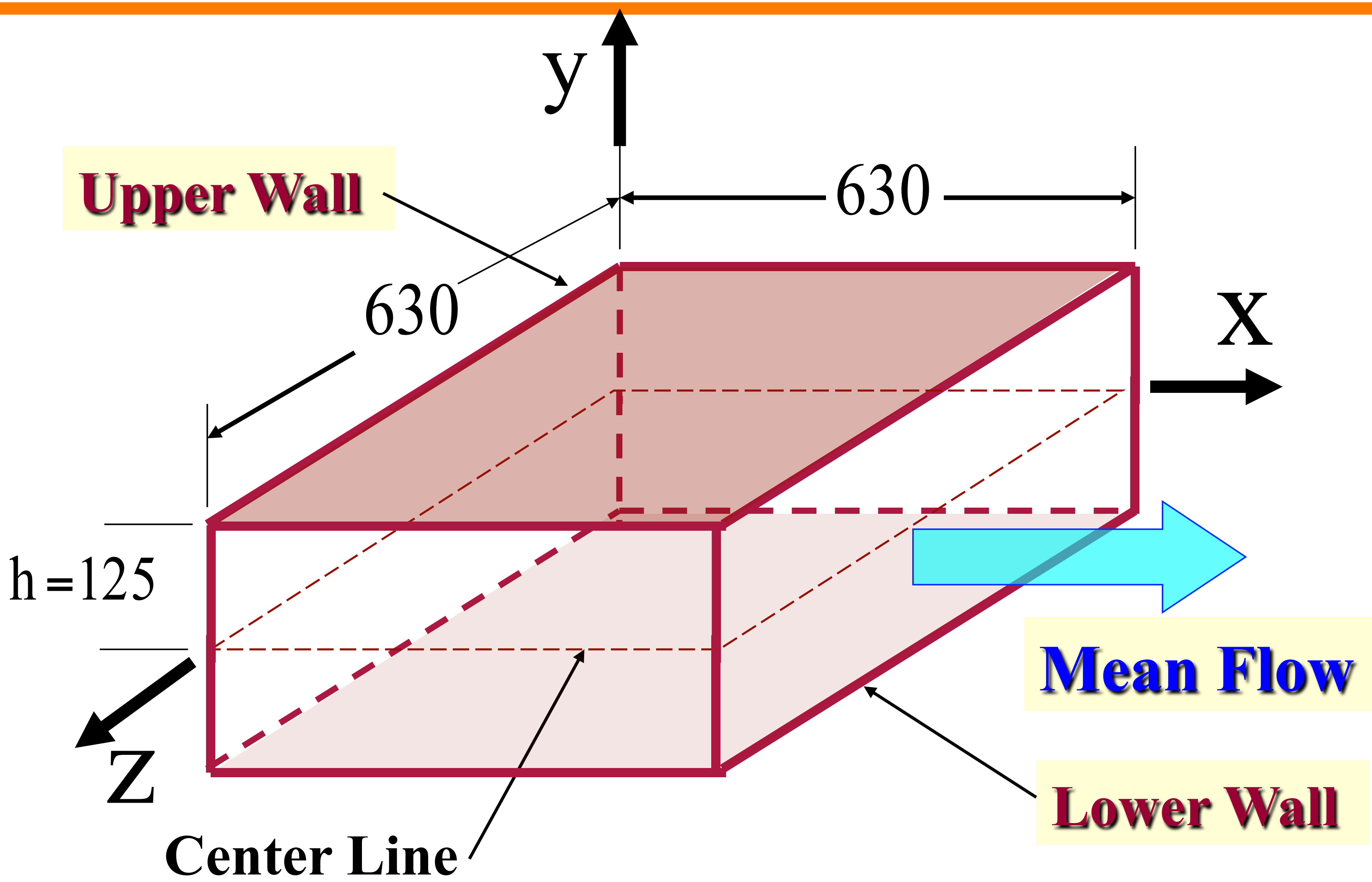
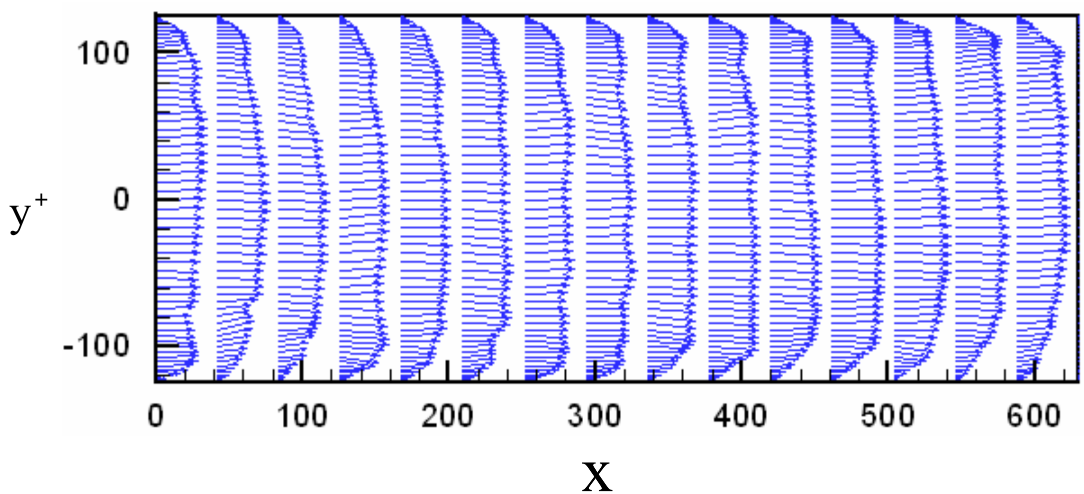
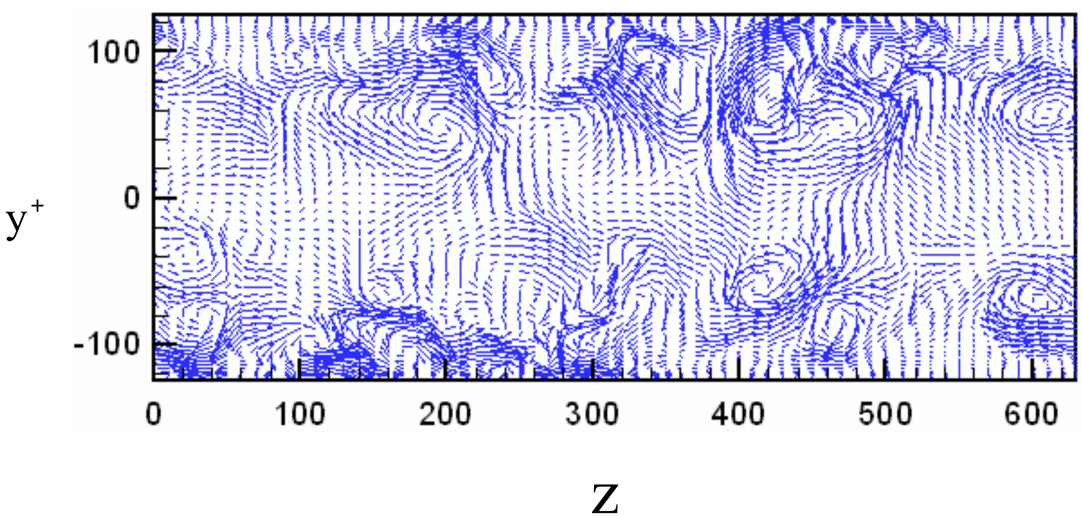


Instantaneous Velocity Field





Flow Field Visualization

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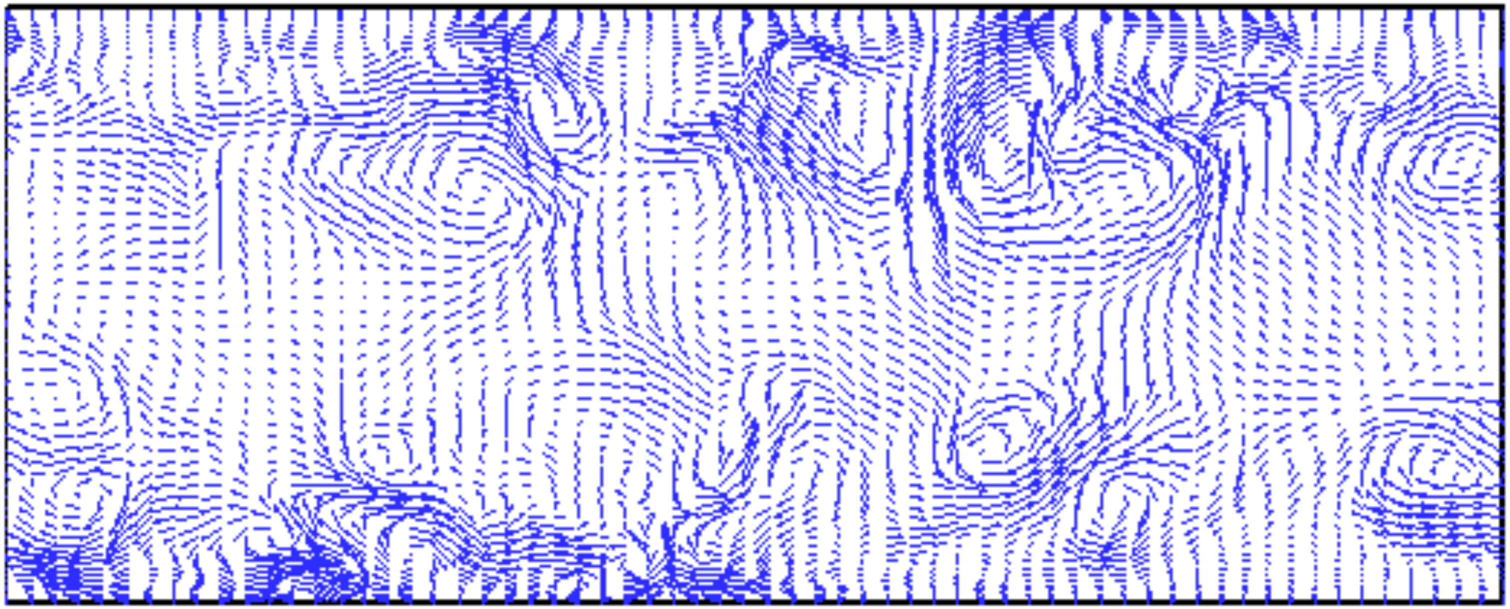

Governing Equations

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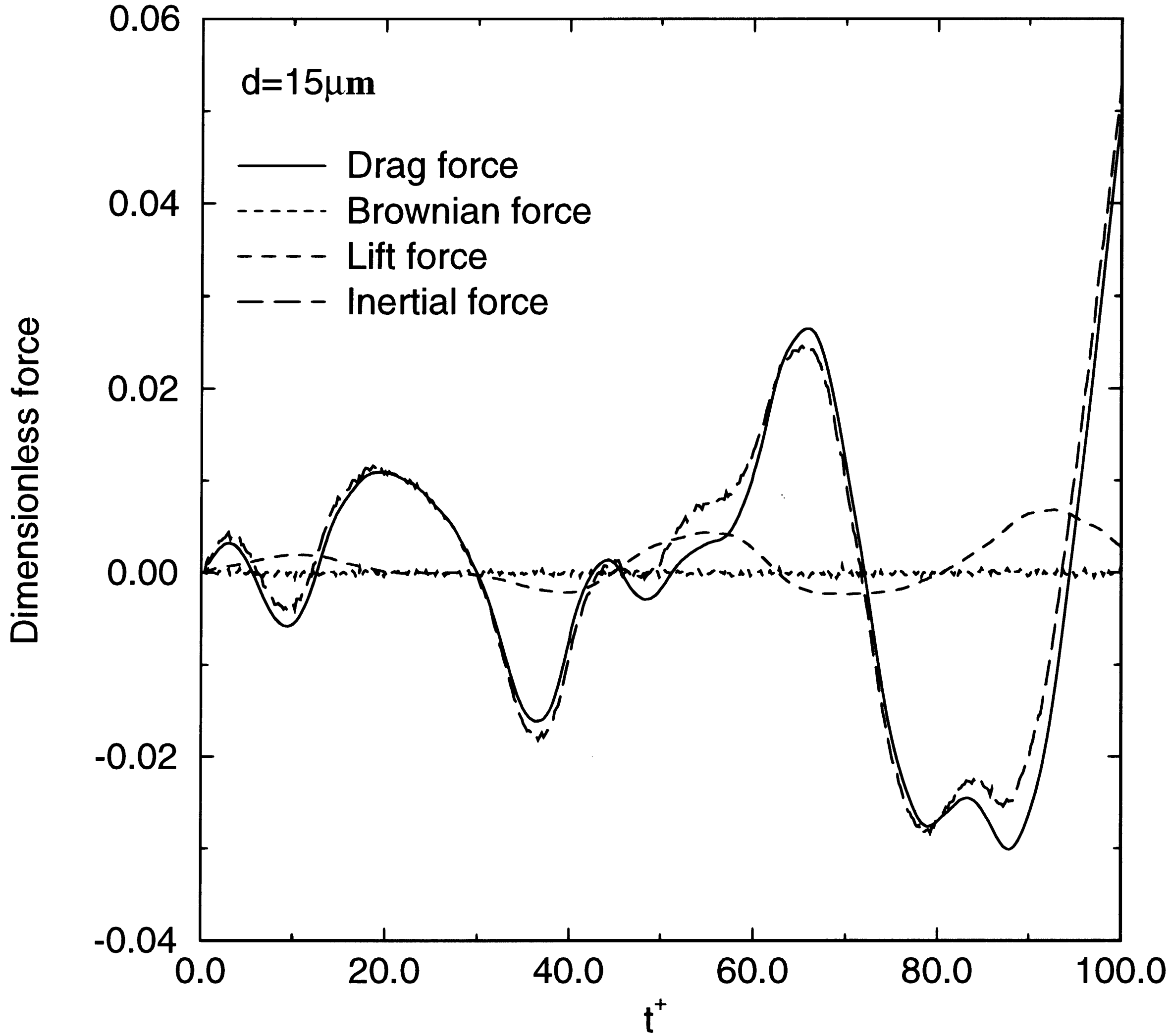
Spherical Particle Equation of Motion

$$\frac{dv^+}{dt^+} = g^+ + F_d^+ + F_L^+ + n^+(t^+)$$

Gravity **Drag** **Lift** **Brownian**

$$\frac{dx^+}{dt} = v^+$$

Comparison of Force Magnitudes



Deposition Pattern

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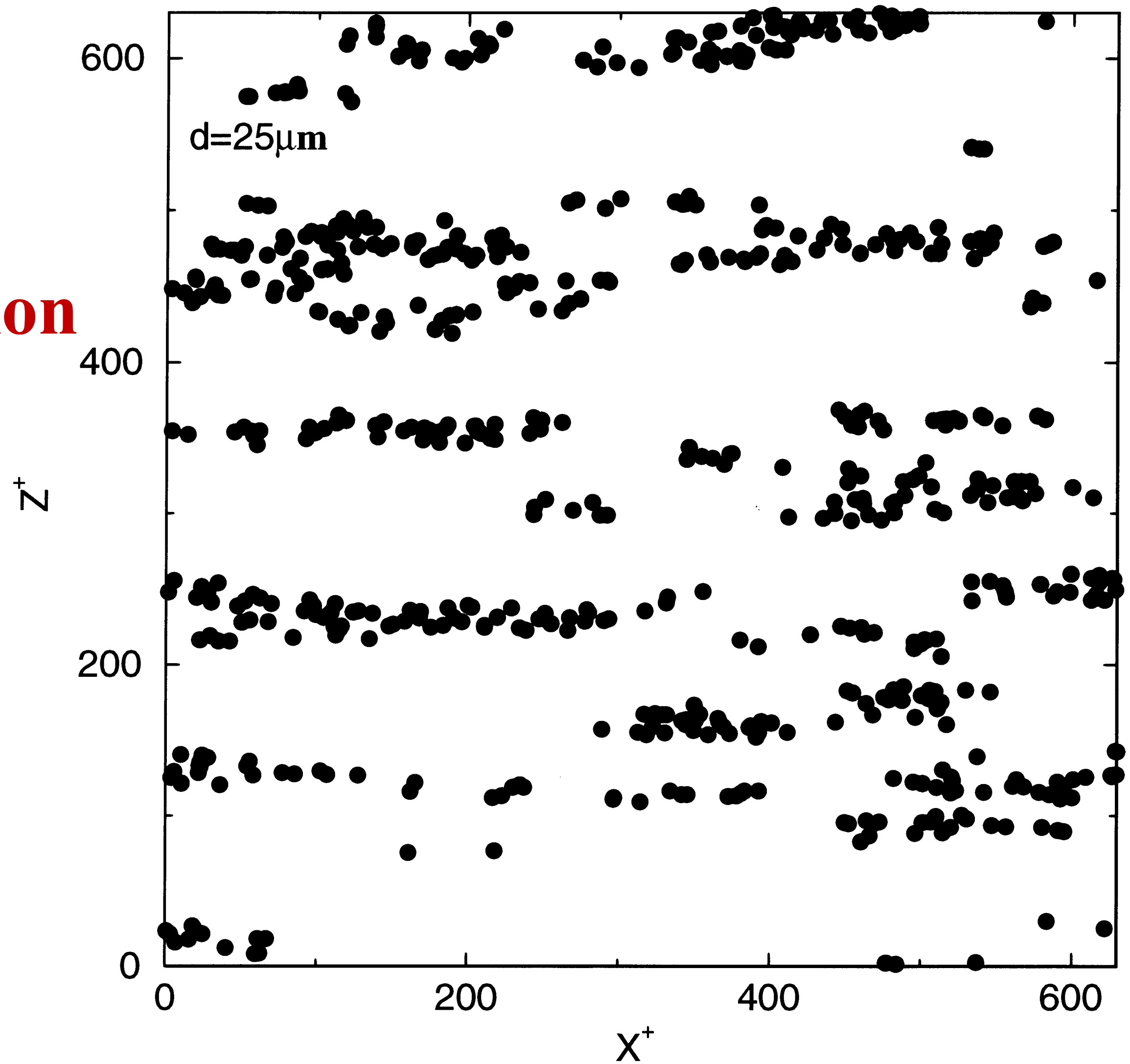
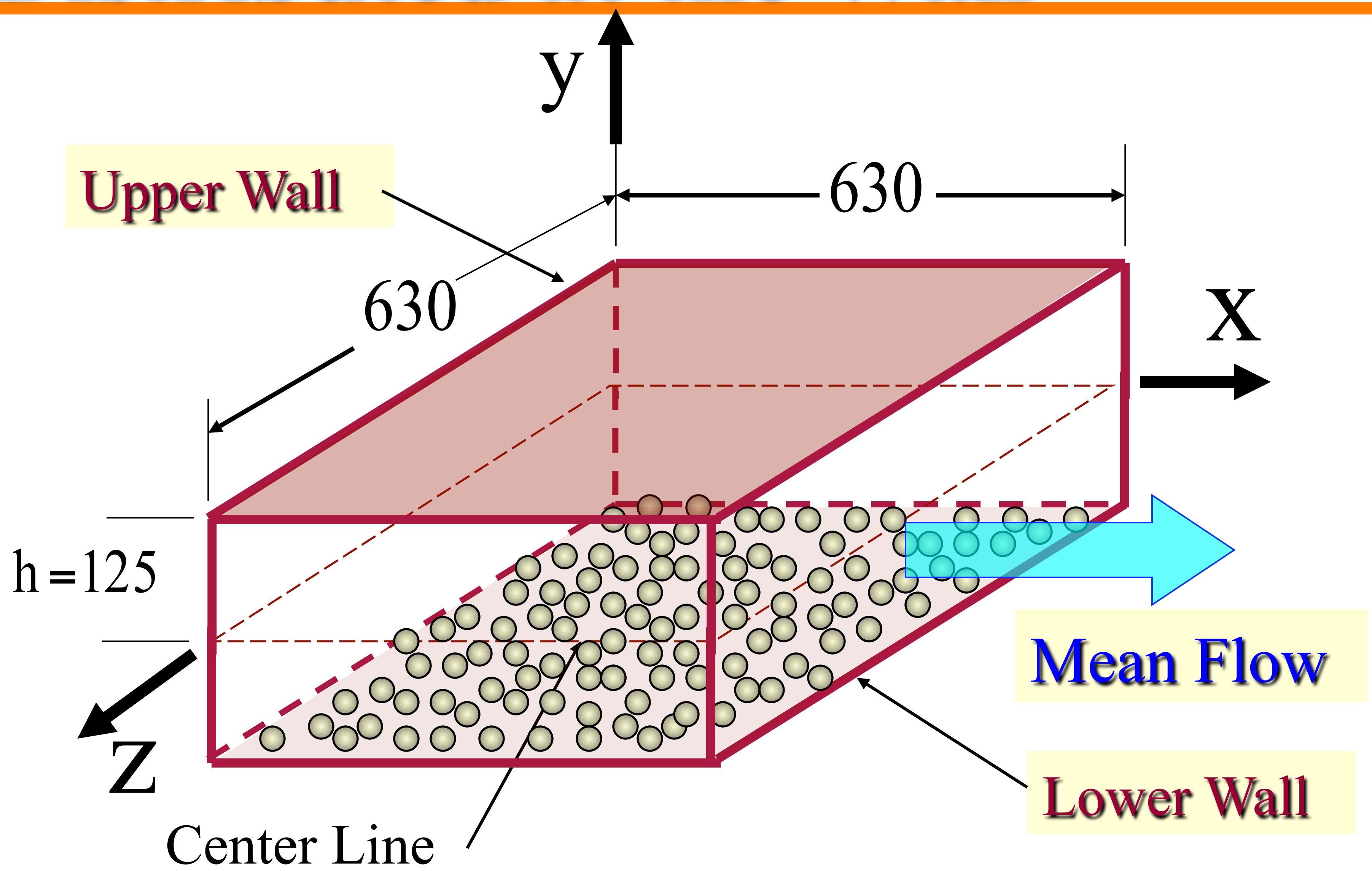
Mean Flow Direction



Particles Are Randomly Distributed at the Wall



Particle Removal Pattern

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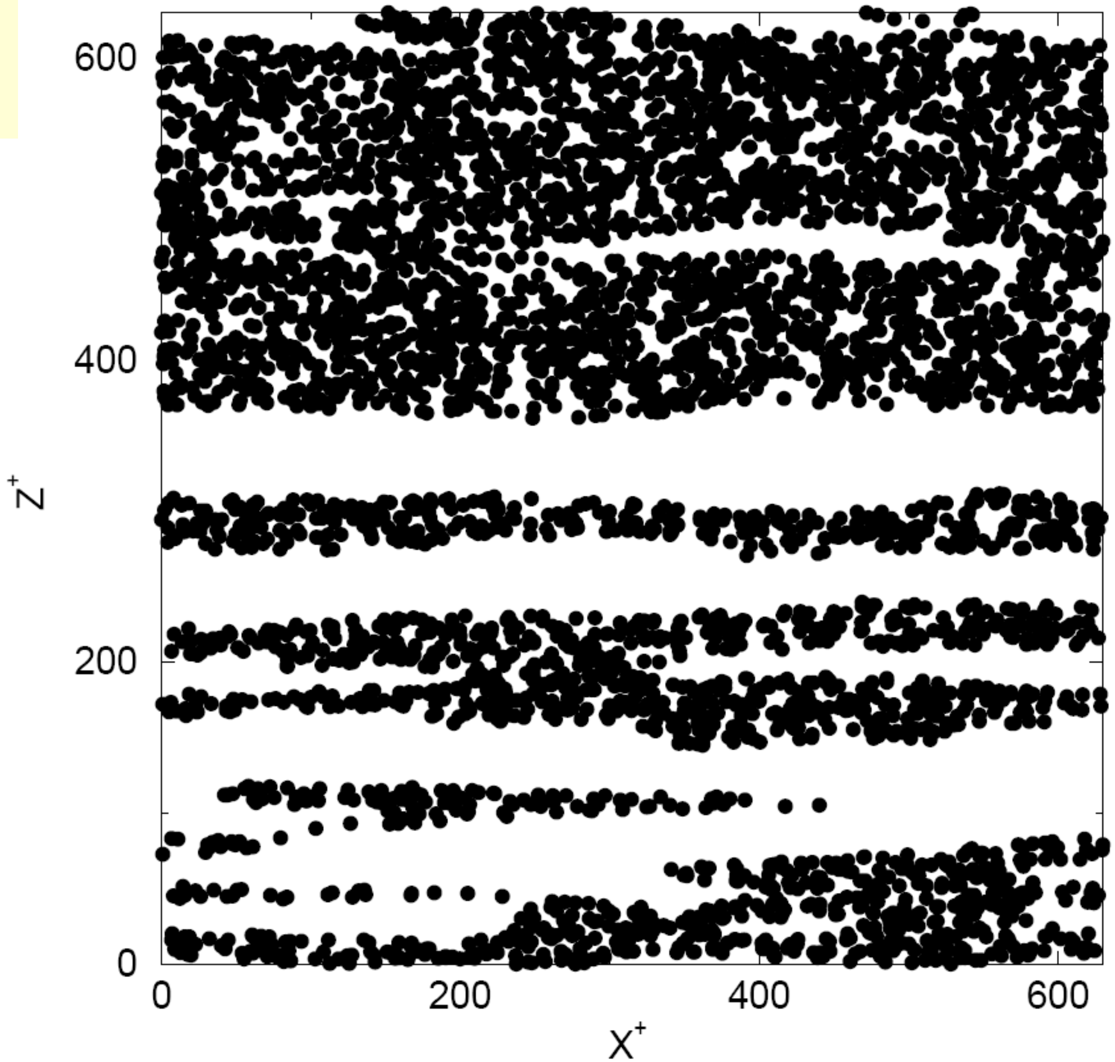
Surface Concentration

$t^+ = 40$

30 μm

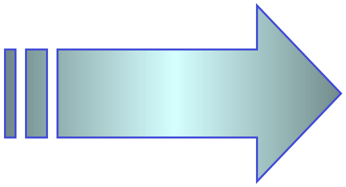


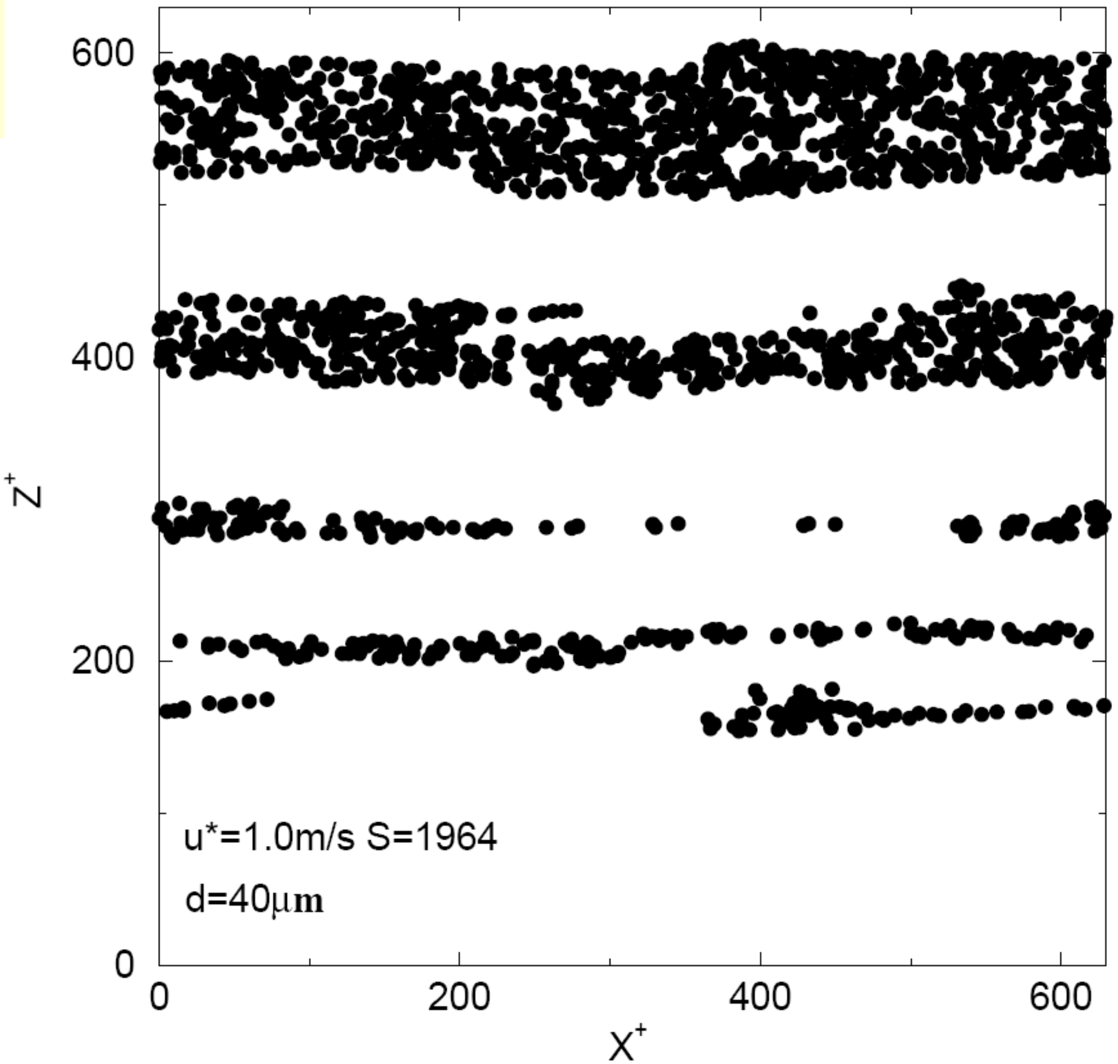
Particle Removal Pattern

Clarkson University

40 μm

Surface Concentration





$t^+ = 40$

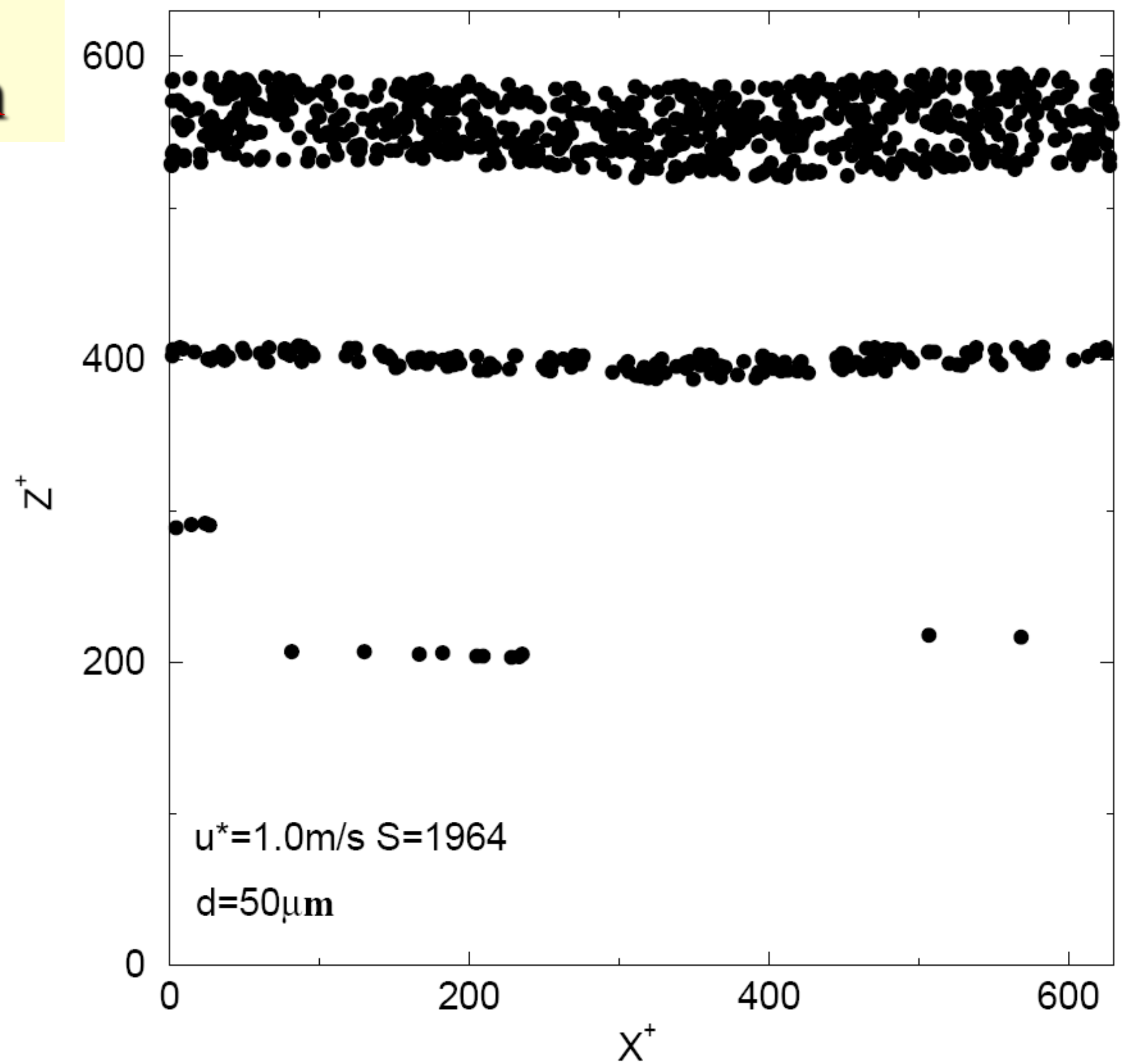
Particle Removal Pattern

Clarkson University

Surface Concentration

$t^+ = 40$

50 μm



Variations of Averaged Velocities

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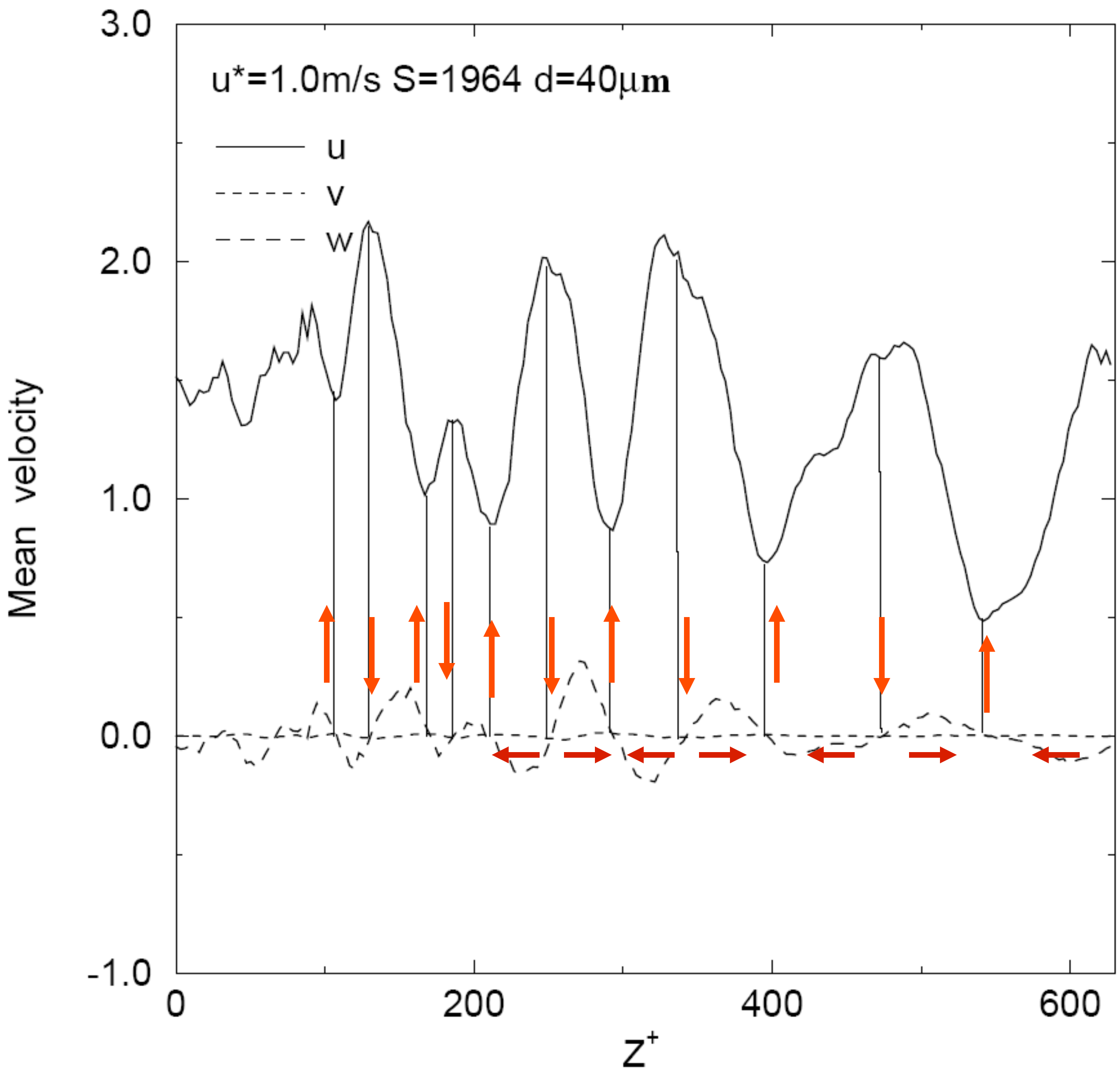

Variation of Averaged V-Velocities

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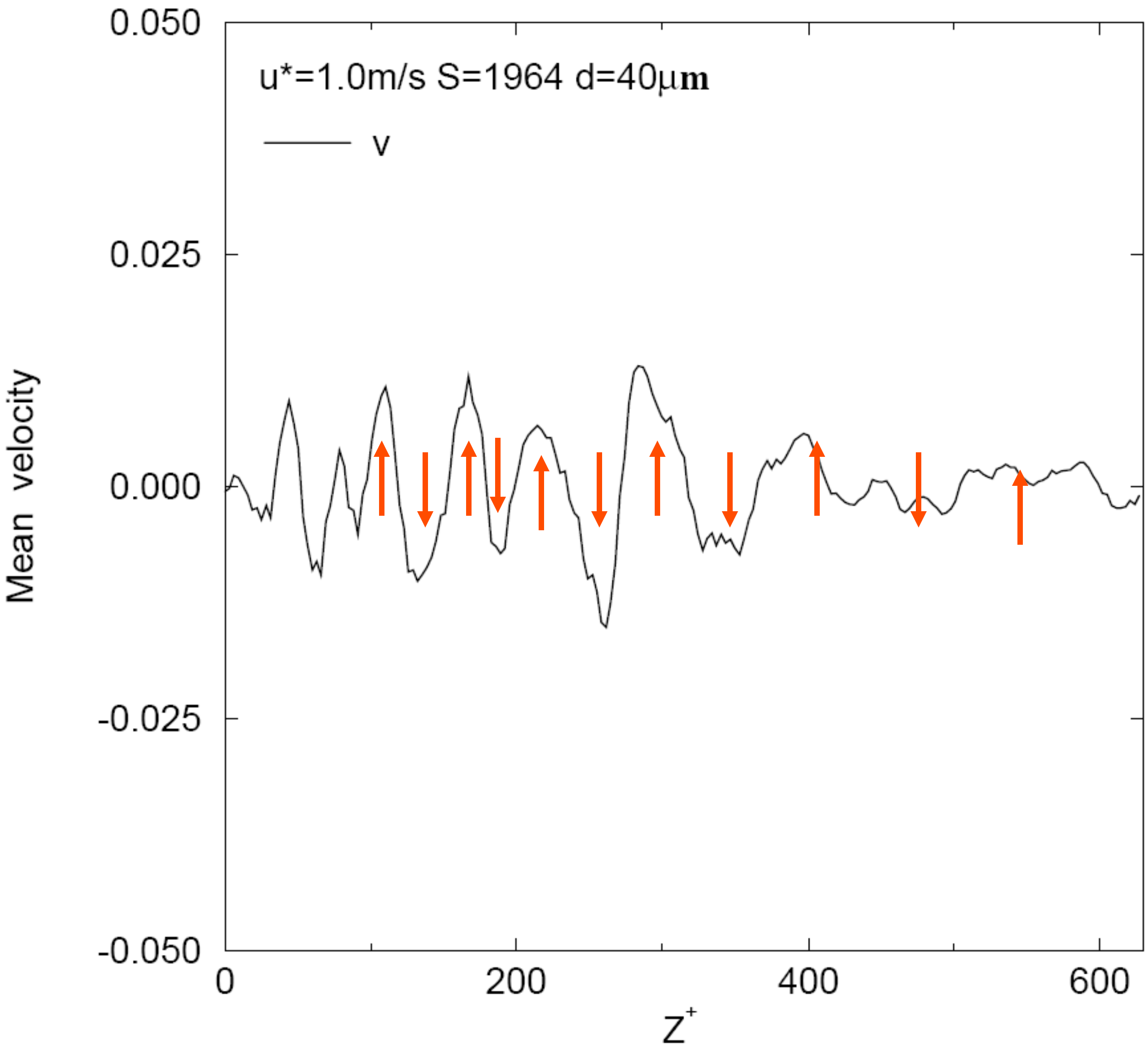

Coherent Wall Vortices

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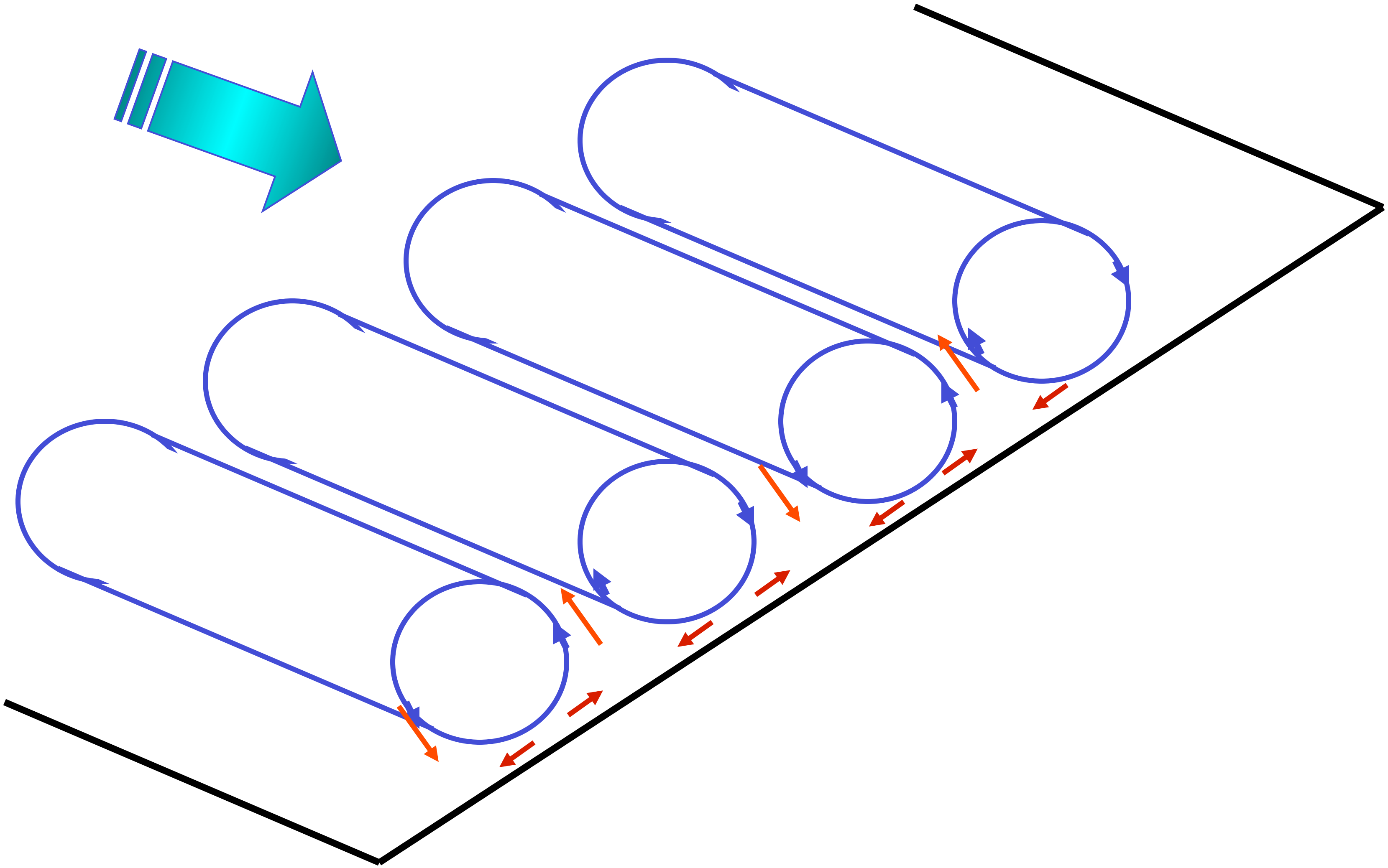

Particle Transport Pattern

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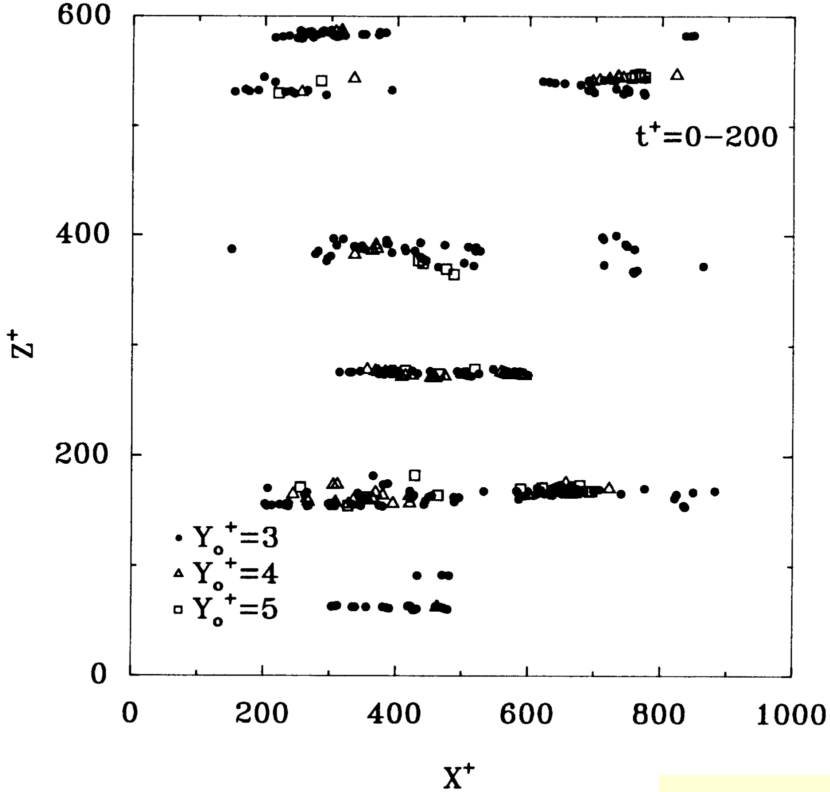
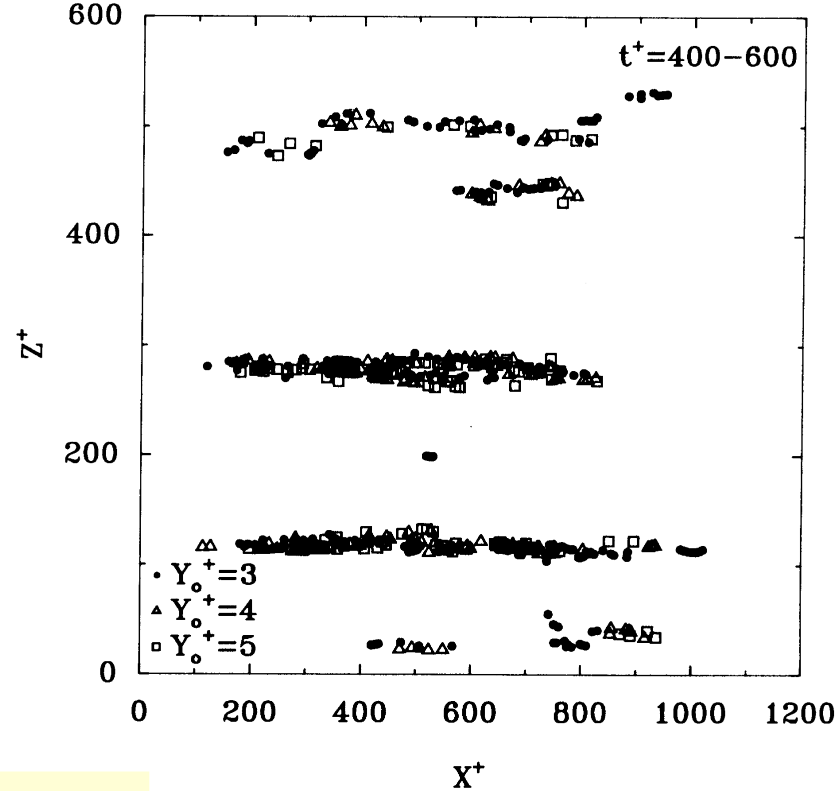
$0 < t^+ < 200$



$400 < t^+ < 600$



d=0.5 μm

Vorticity Variations

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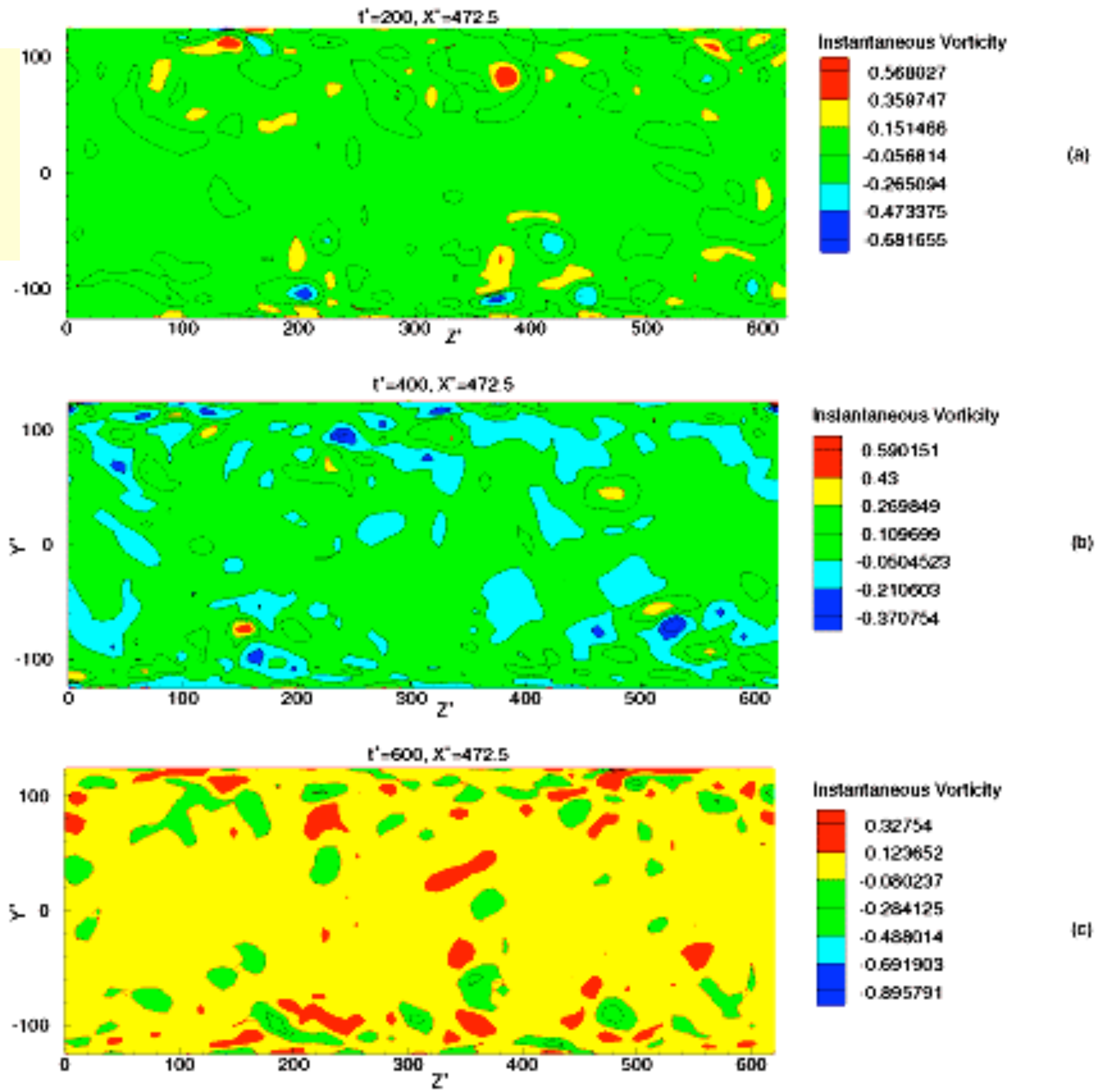
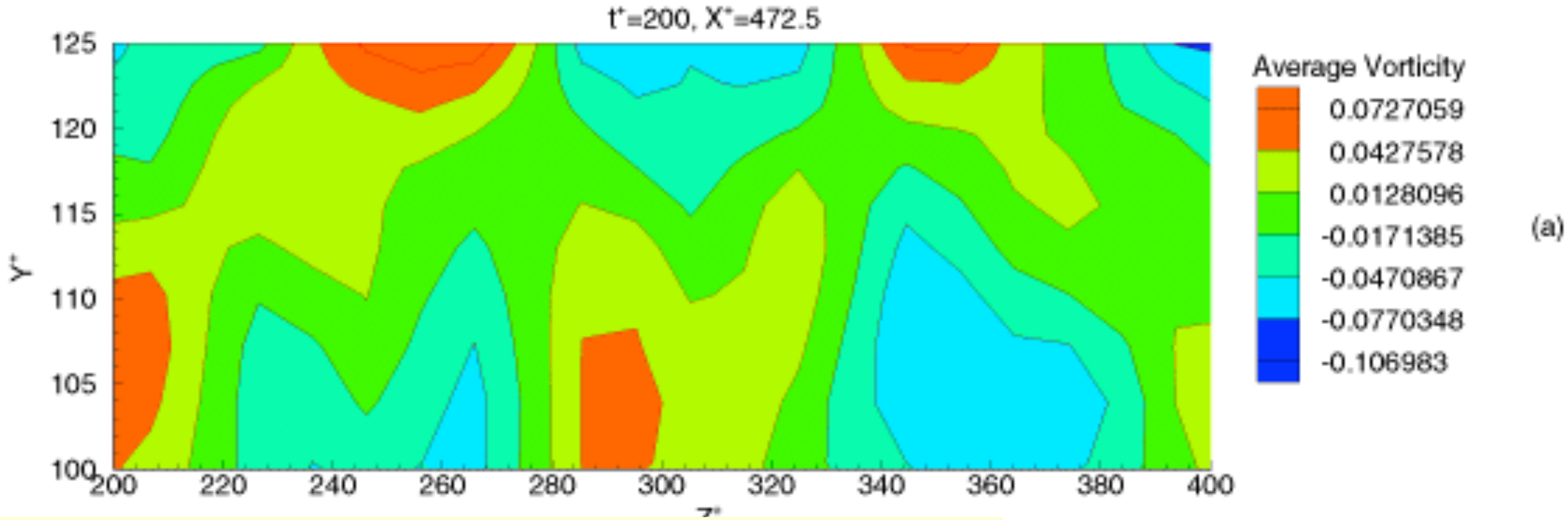
Instantaneous Vorticity

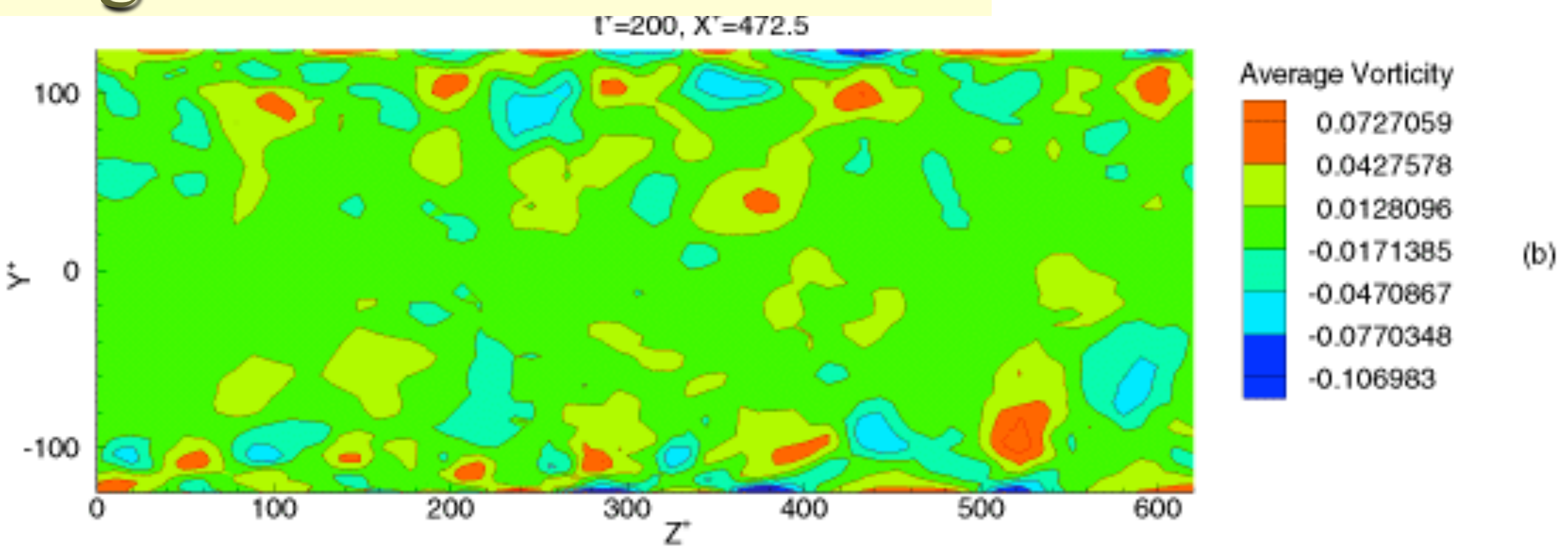


Vorticity Variations

Clarkson University

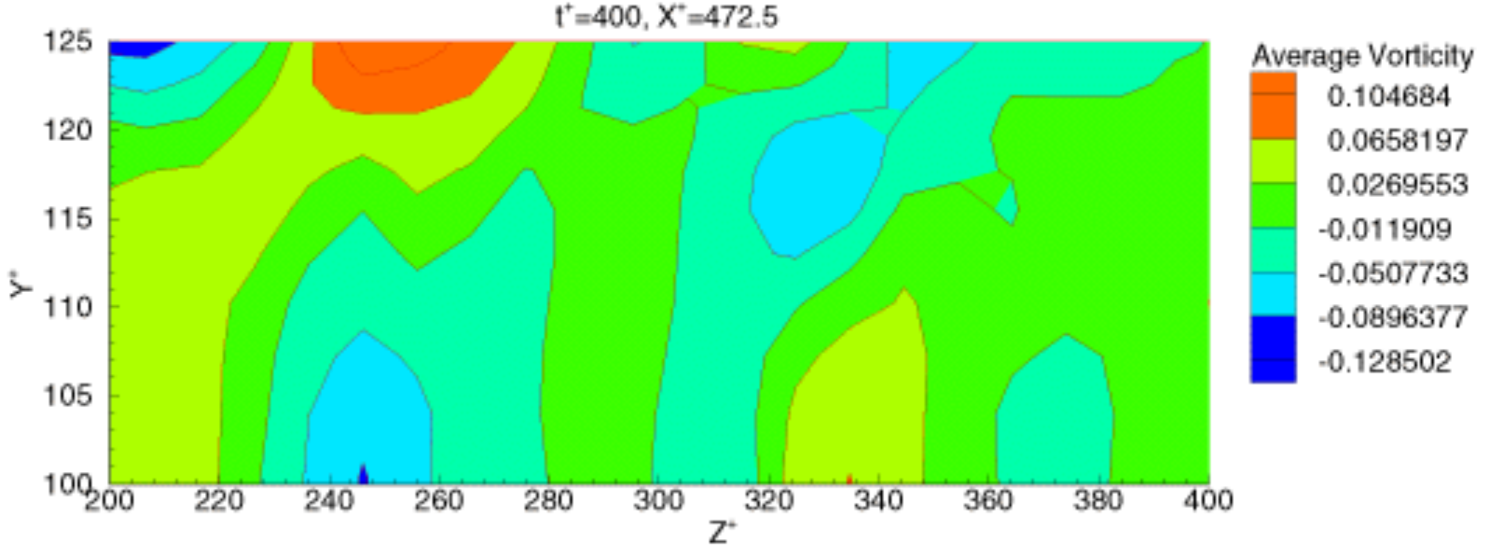


Averaged Over 50 Wall Units

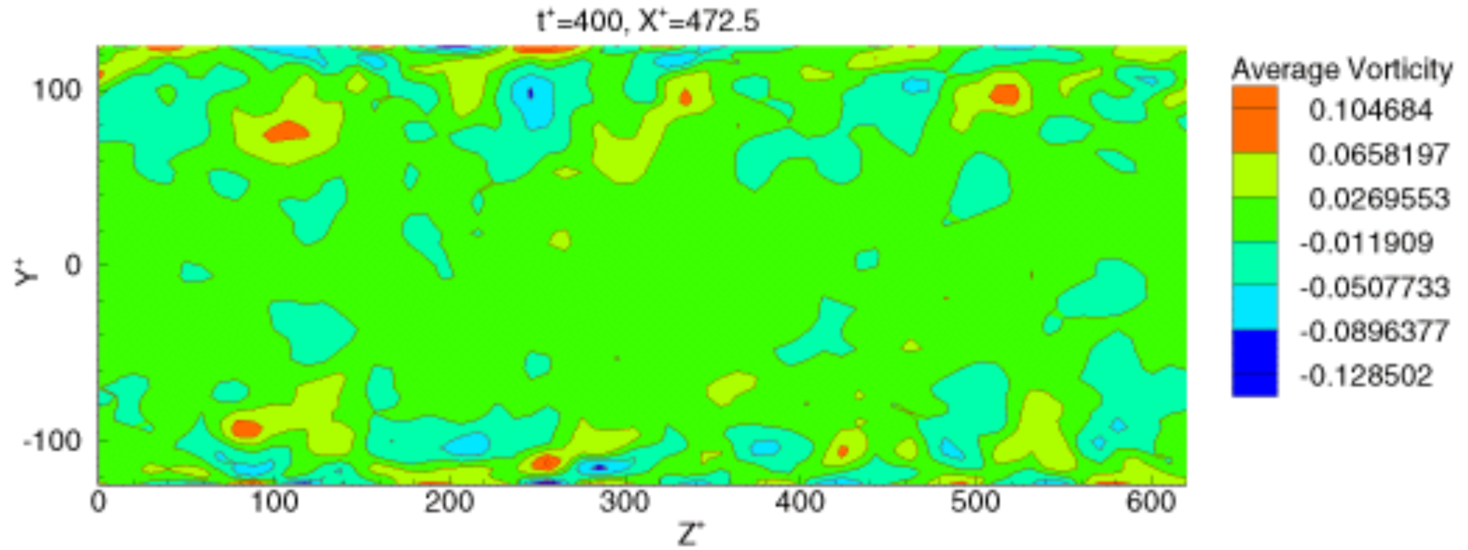


Vorticity Variations

Clarkson University



(a)



(b)

Vorticity Variations

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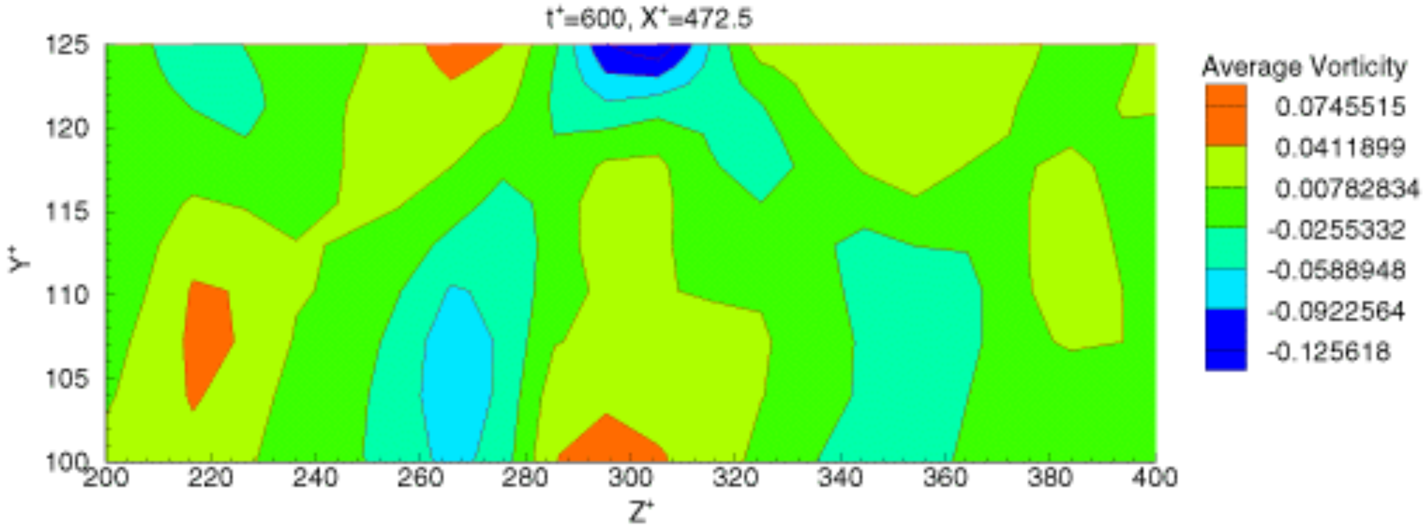
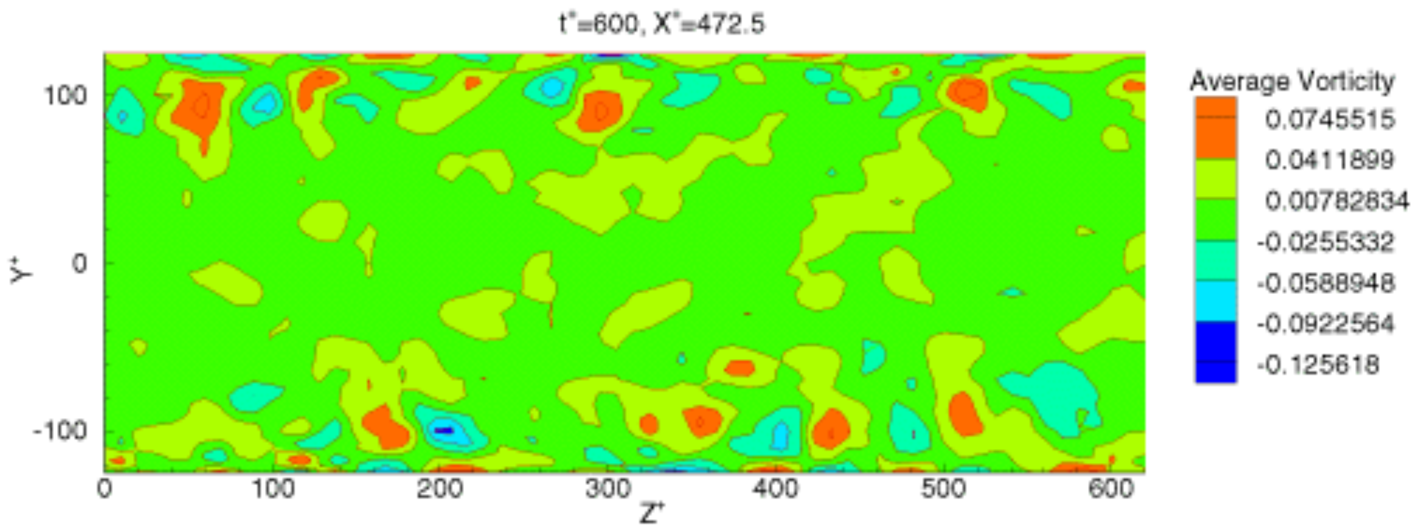


(a)



(b)

Particle Removal Pattern

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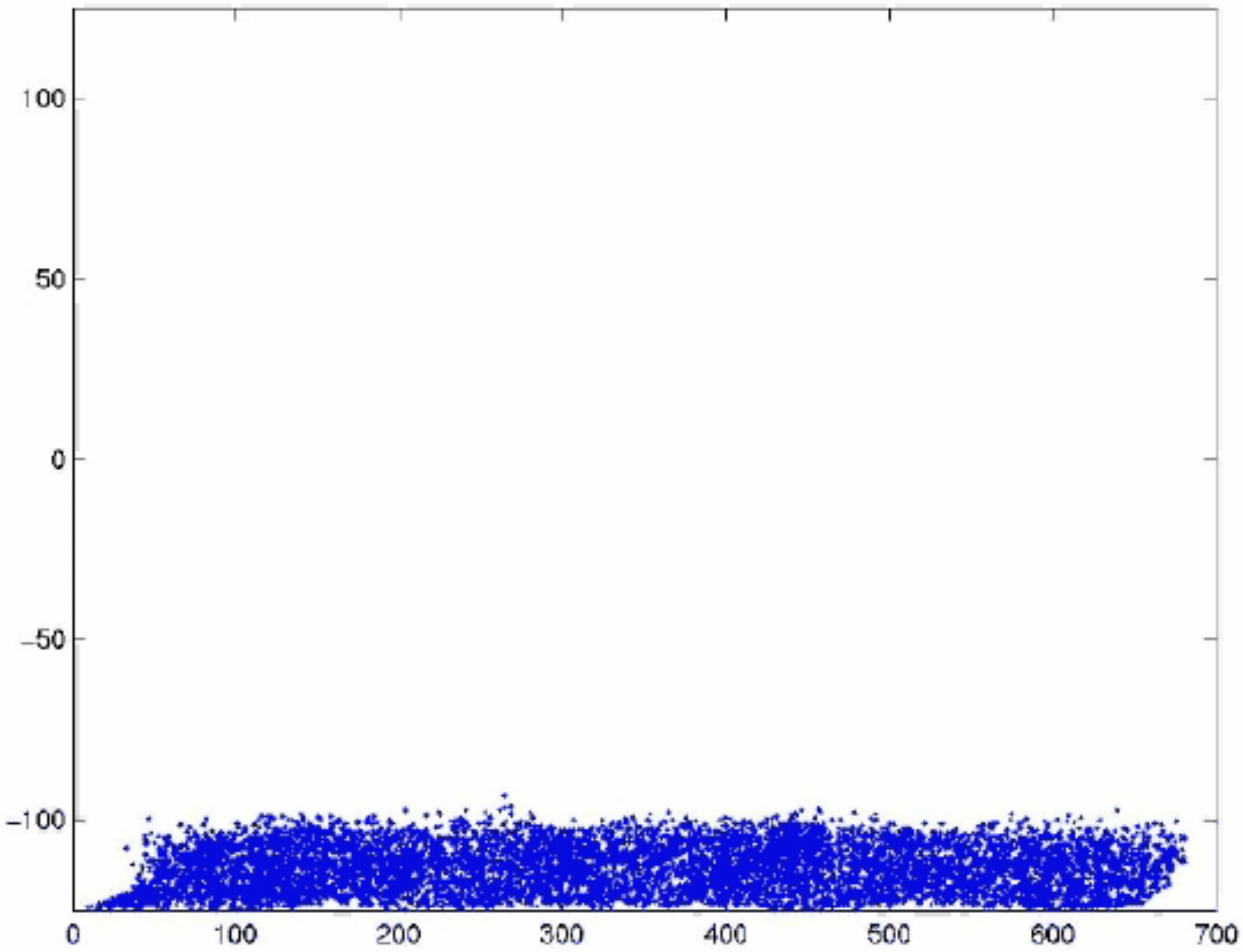
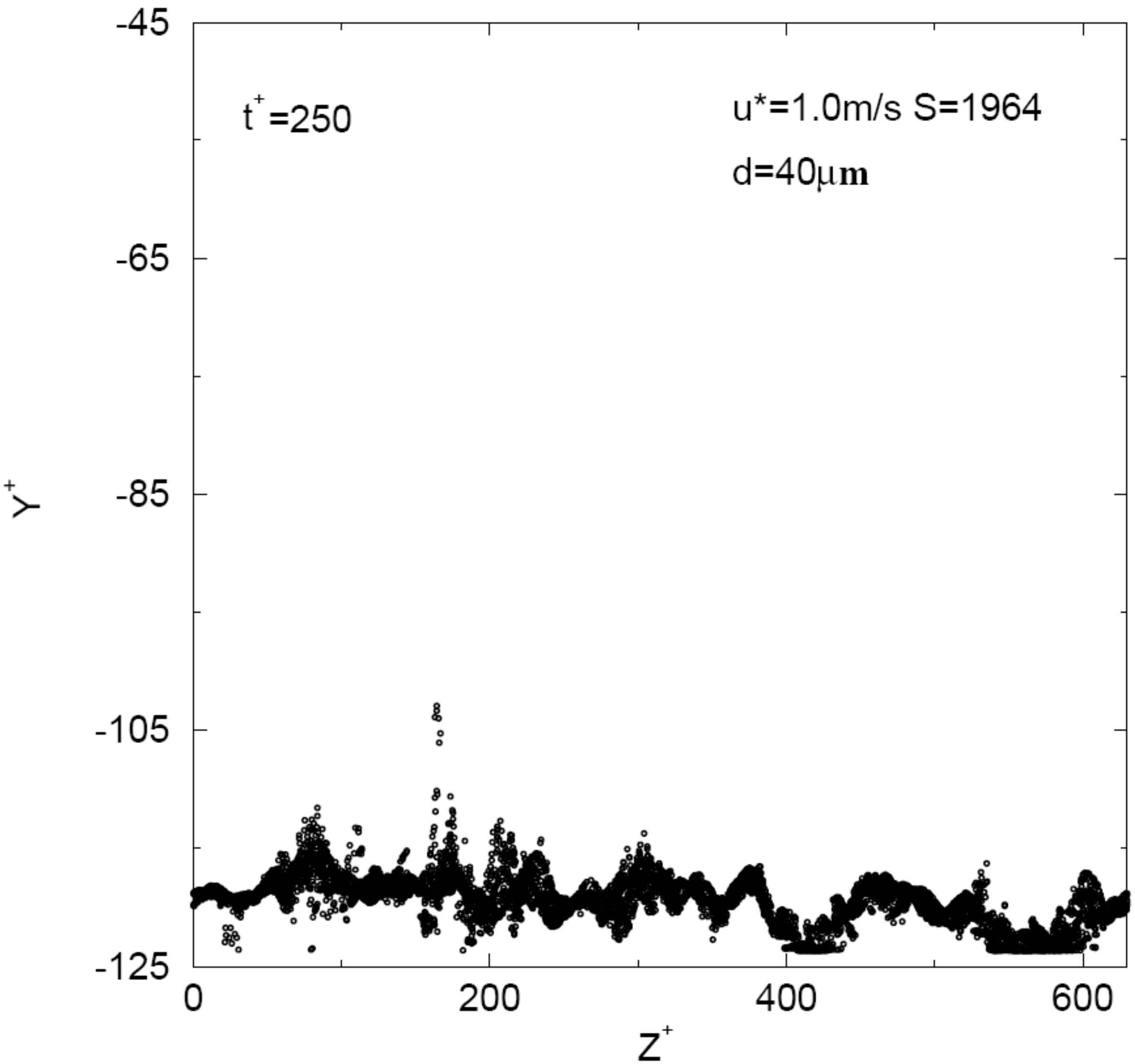


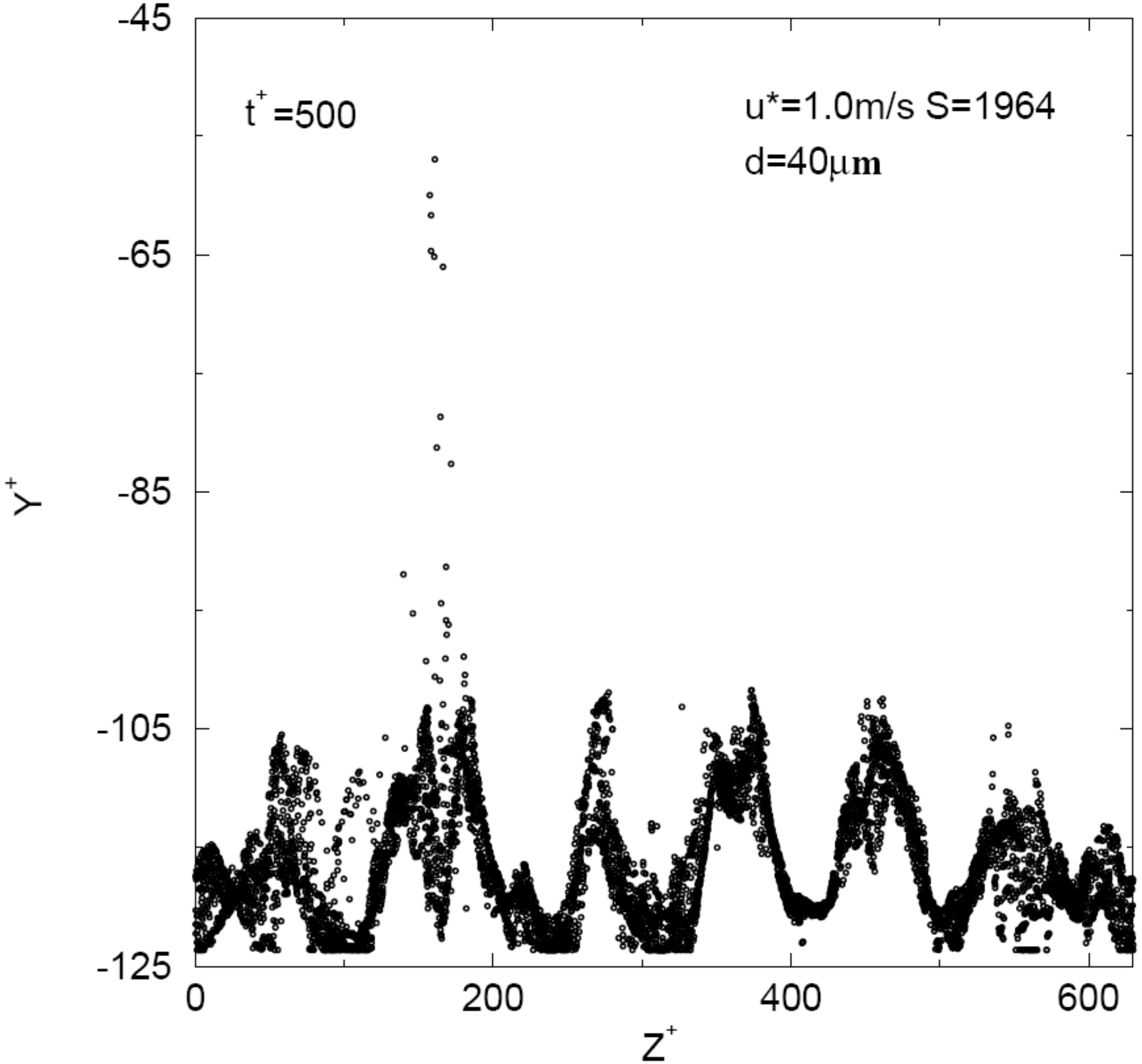
Particle Removal Pattern

Clarkson University



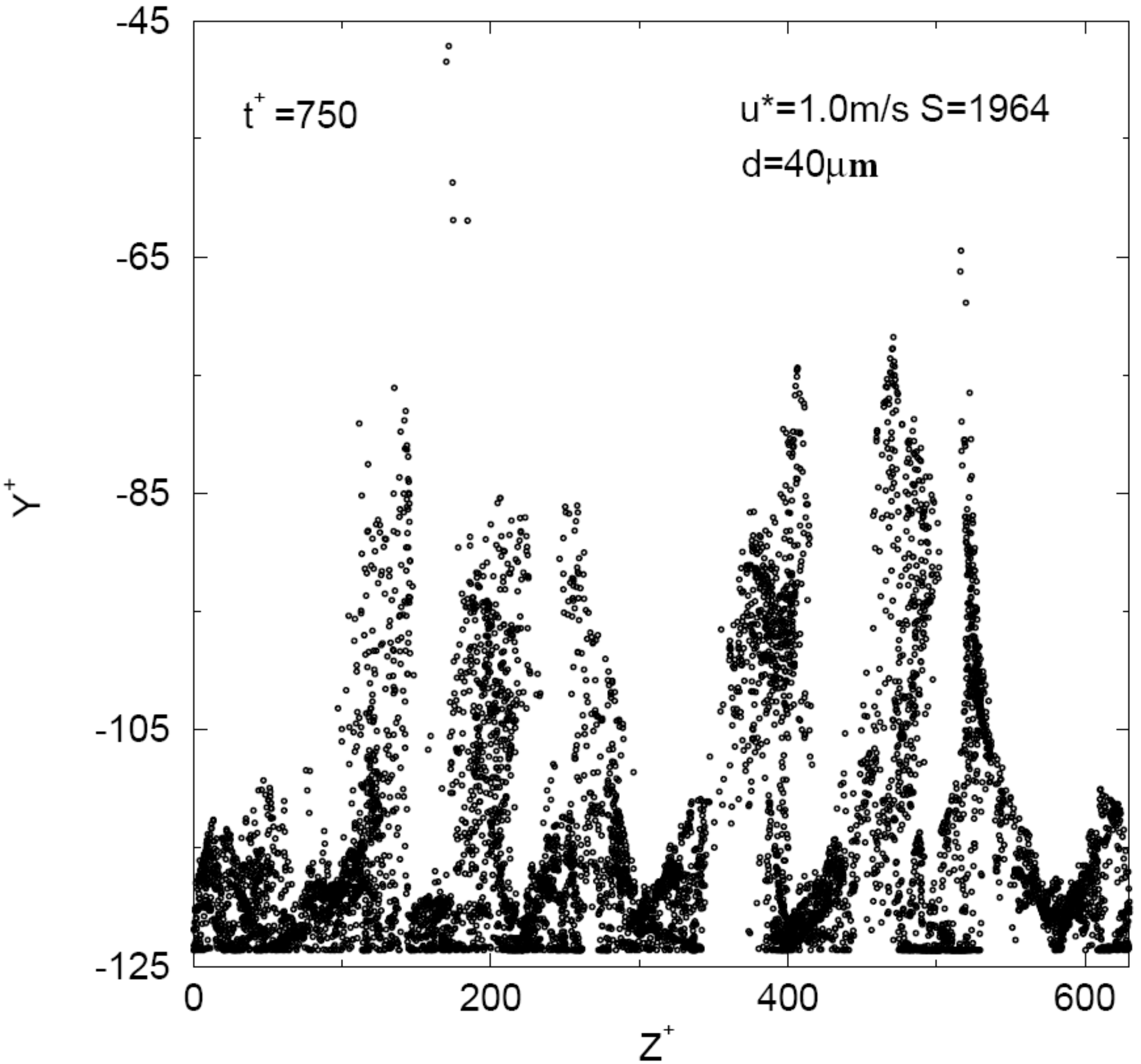
Particle Removal Pattern

Clarkson University



Particle Removal Pattern

Clarkson University



High Speed Streaks

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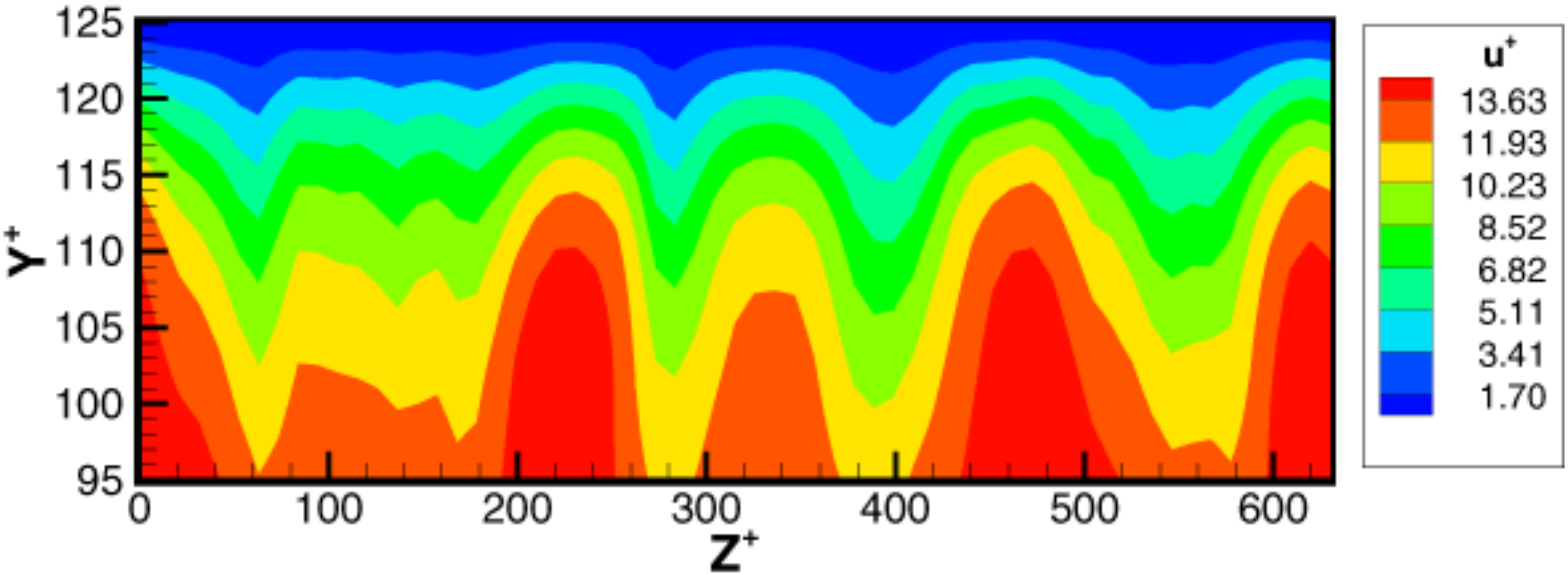

Periodic Vertical Streams

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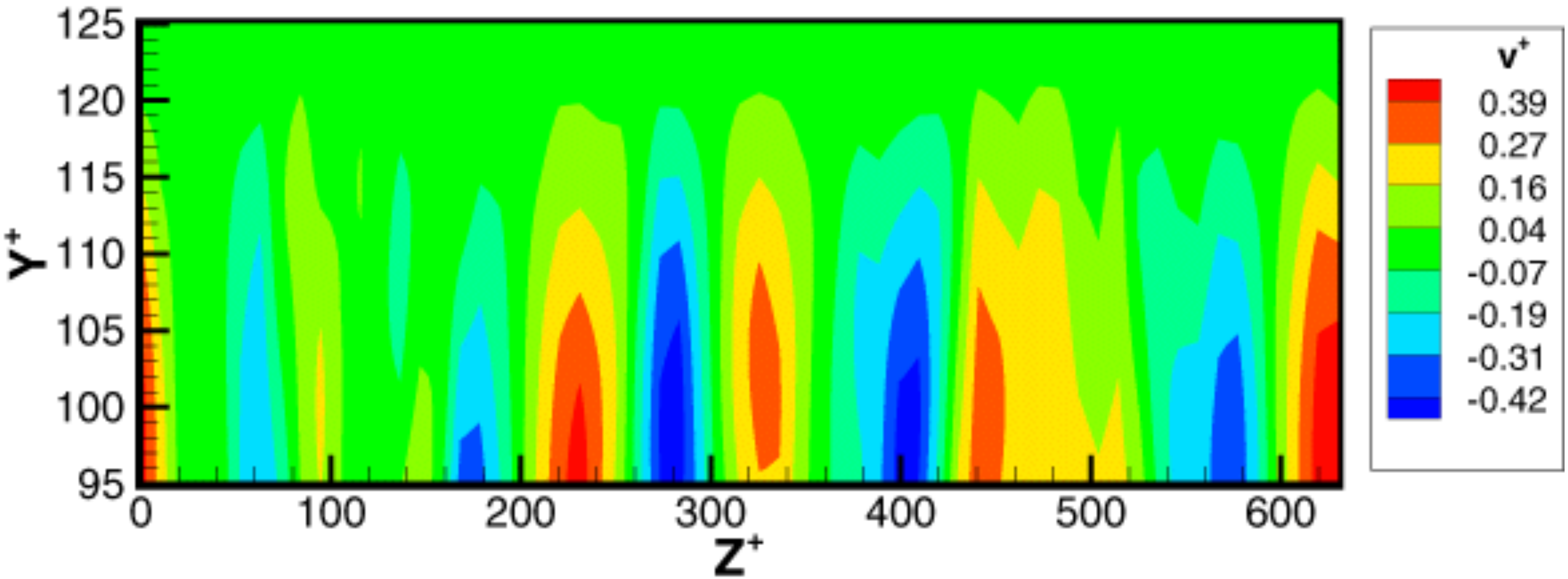
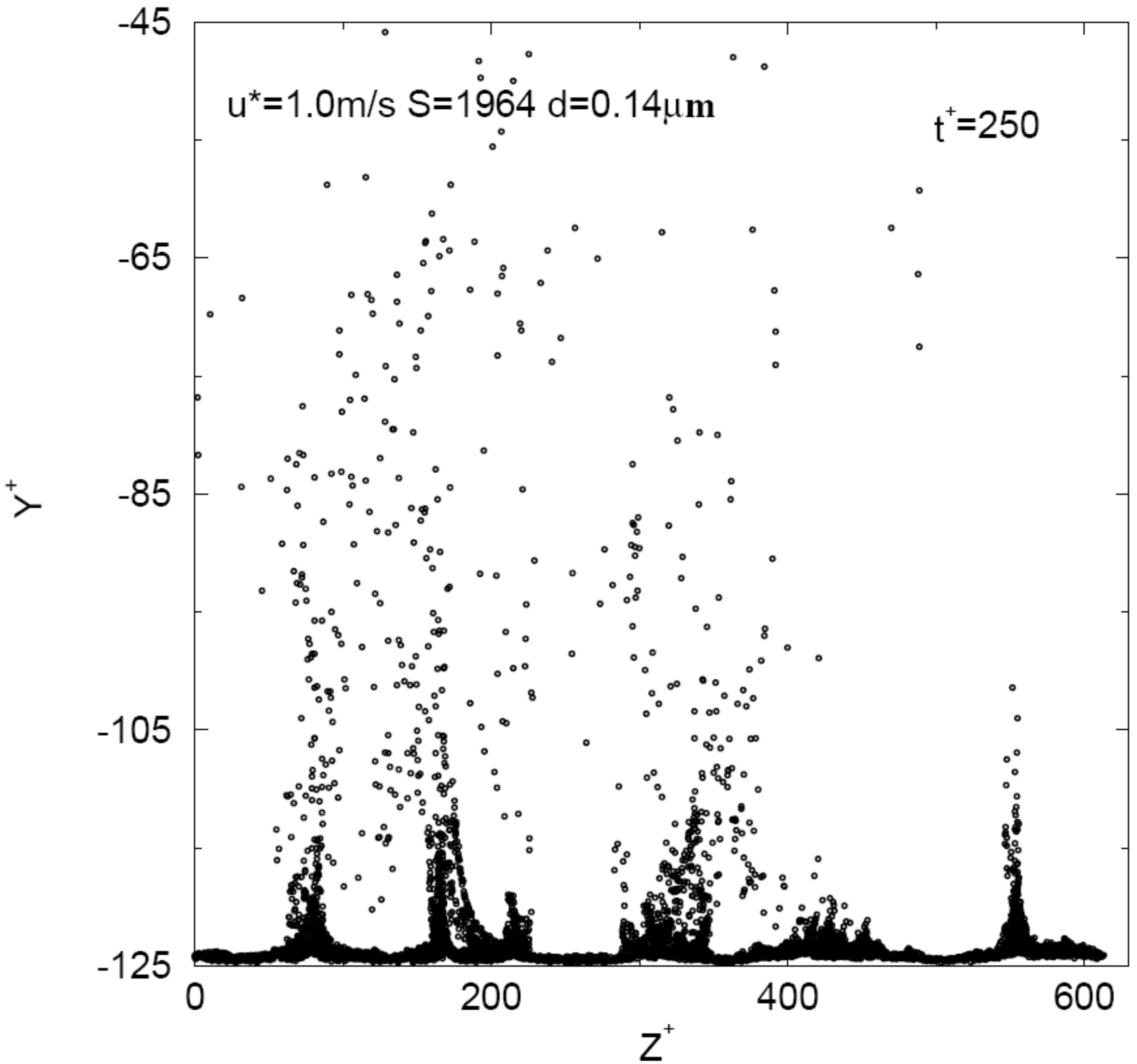
Averaged over 50 time steps



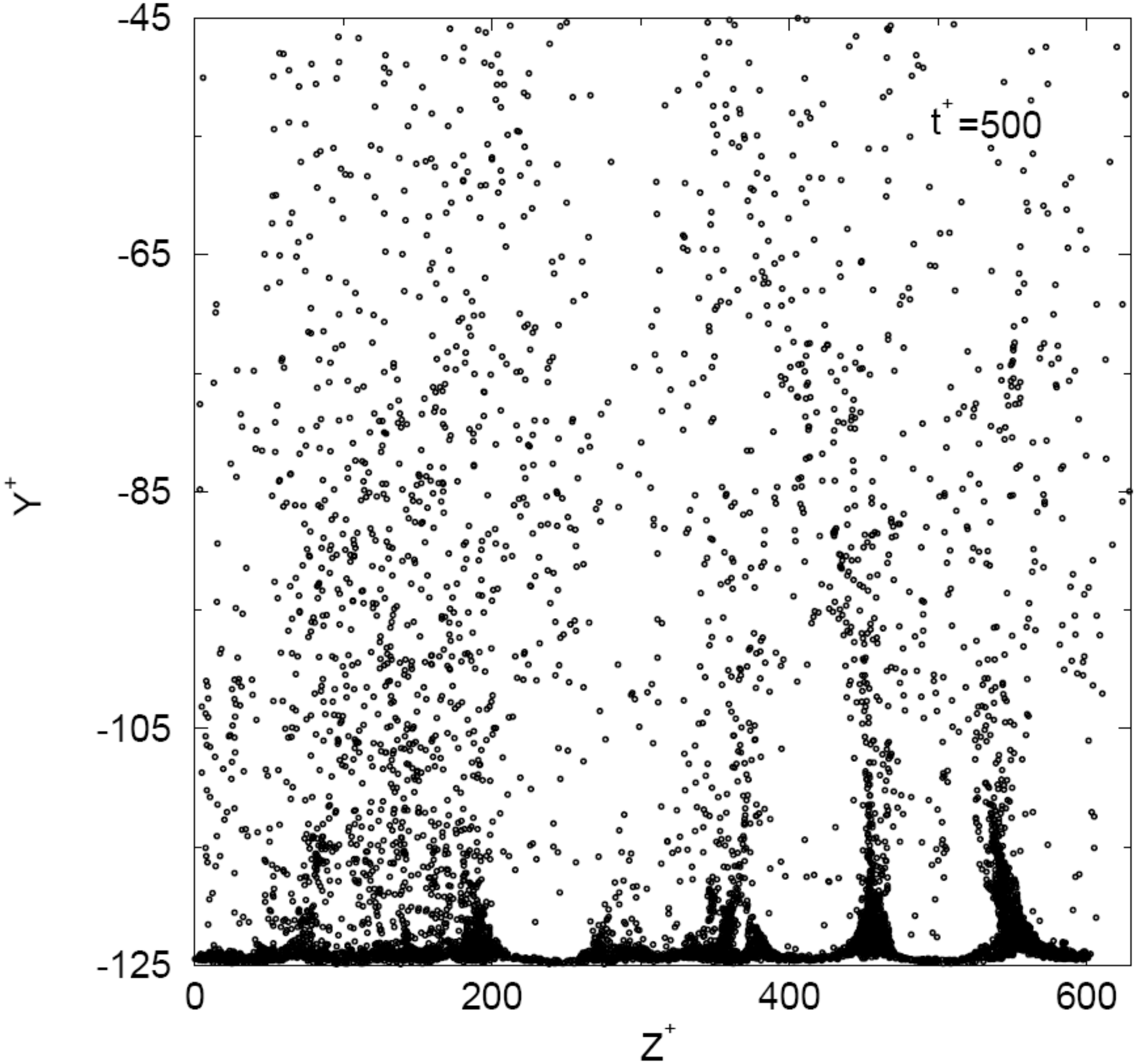
Particle Removal Pattern

Clarkson University



Particle Removal Pattern

Clarkson University



Deposition Velocity

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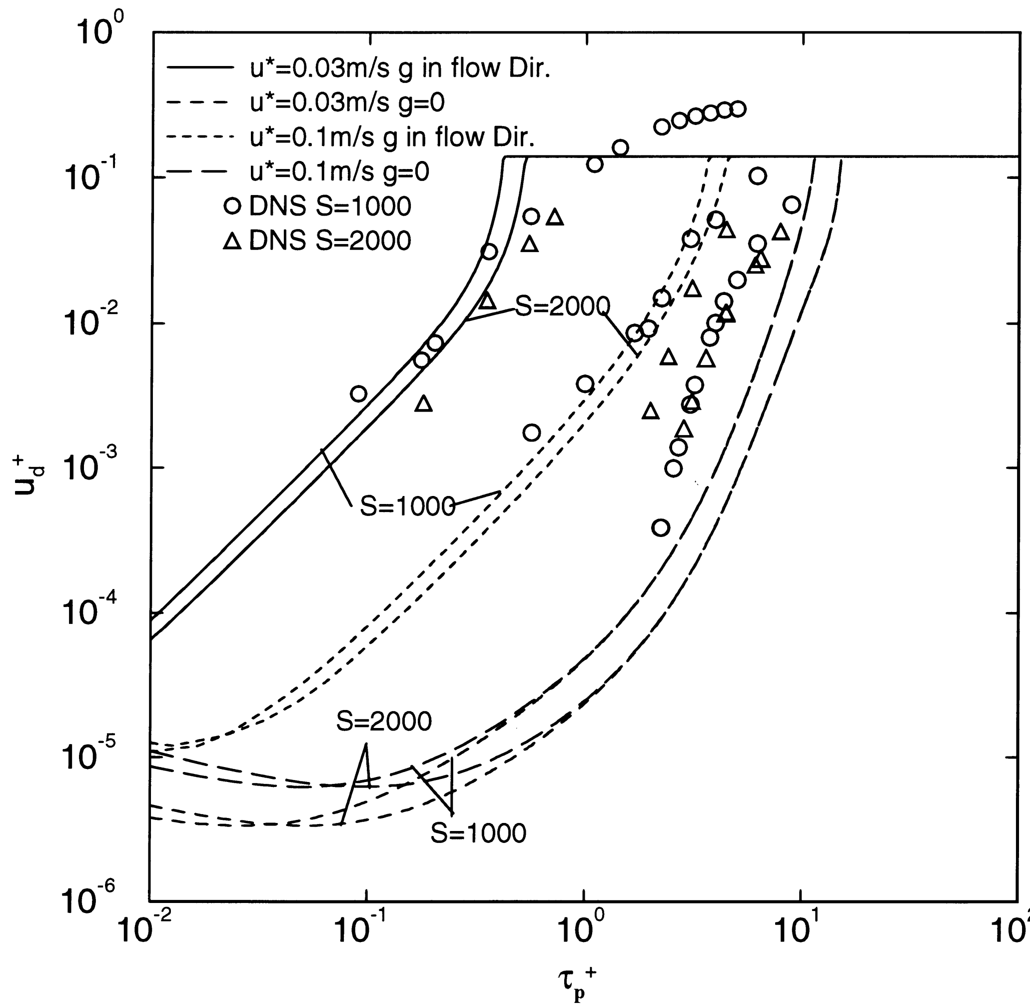
Vertical Ducts

Effects of Shear Velocity and Density Ratio

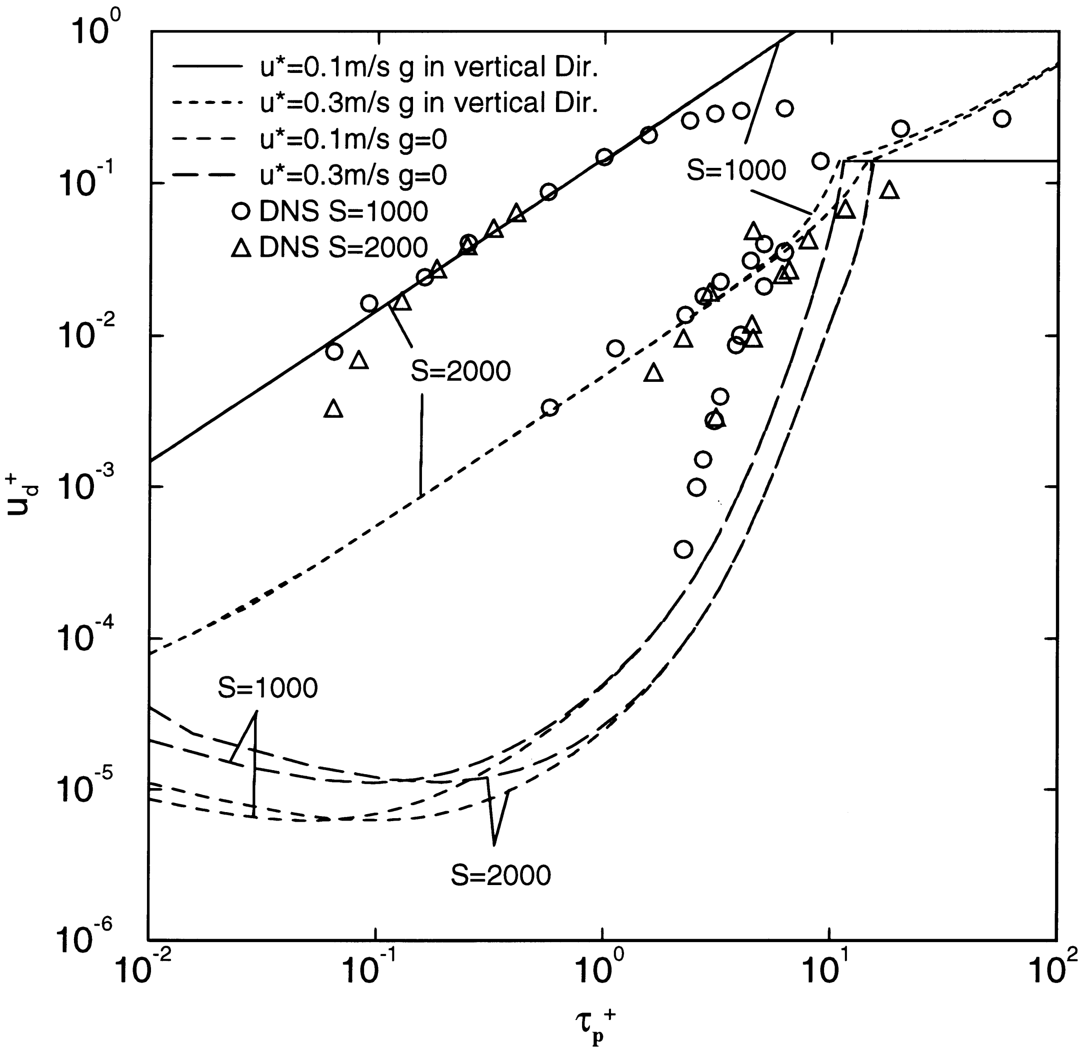


Deposition Velocity

Clarkson University

Horizontal Ducts

Effects of Shear Velocity and Density Ratio



RMS Velocities

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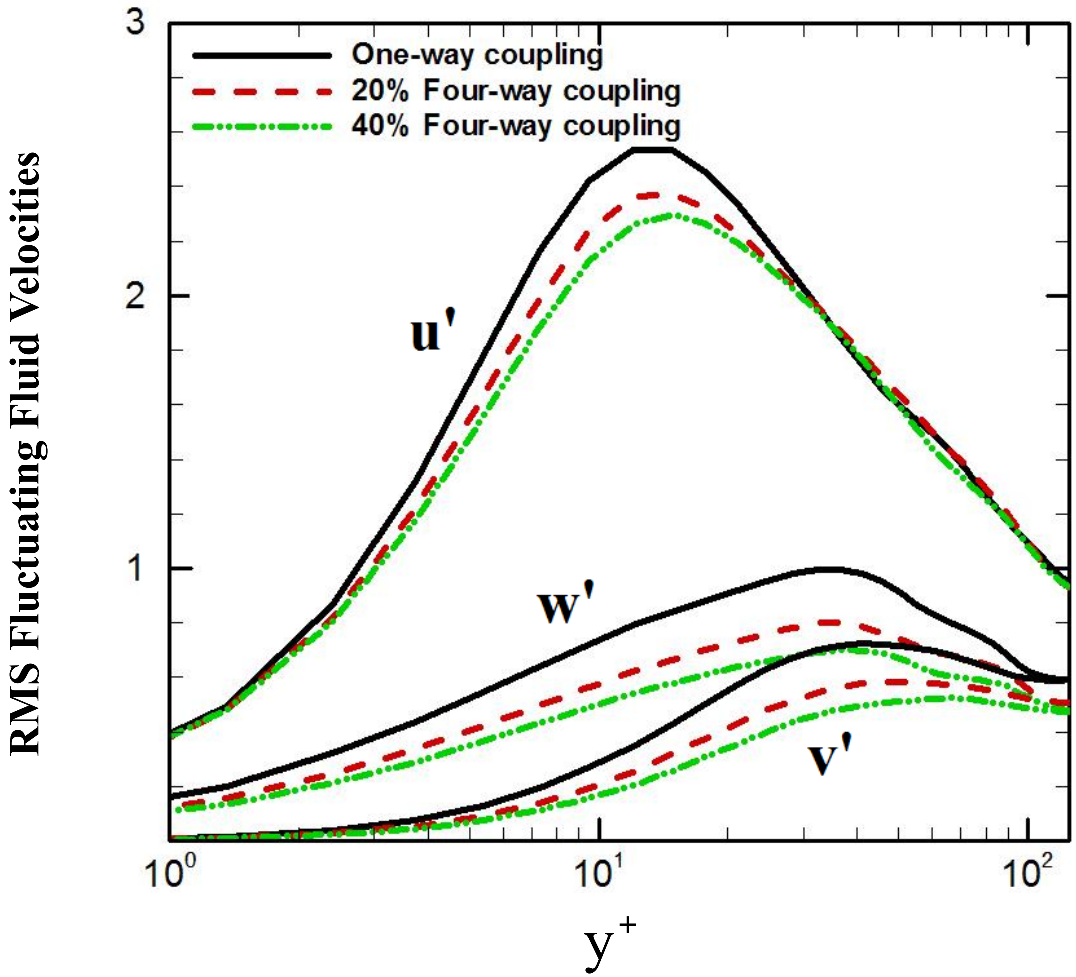

Effects of d=30 micron particles on the flow fluctuating velocities.

Sample Velocity Vector Plots

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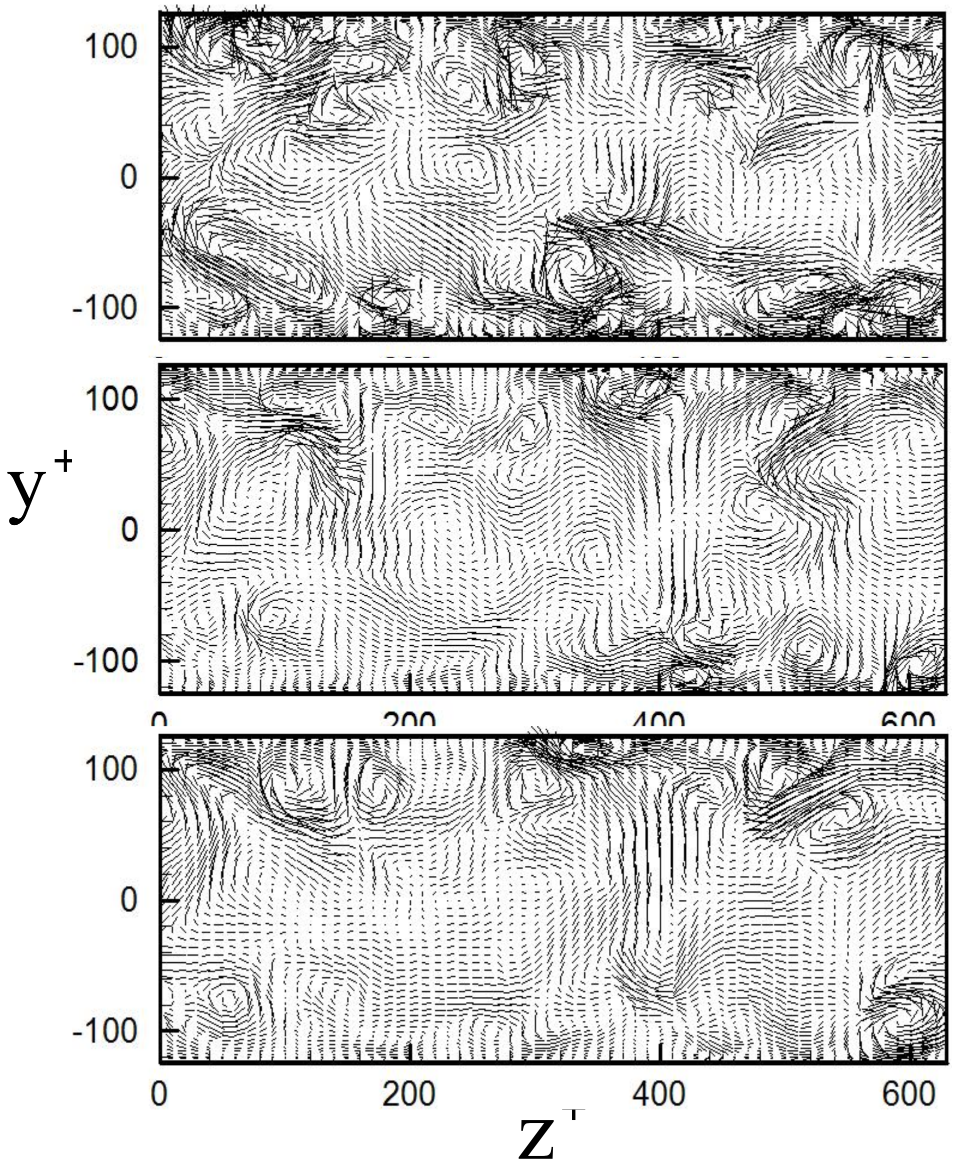

One-way coupling

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

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

Particle Distribution

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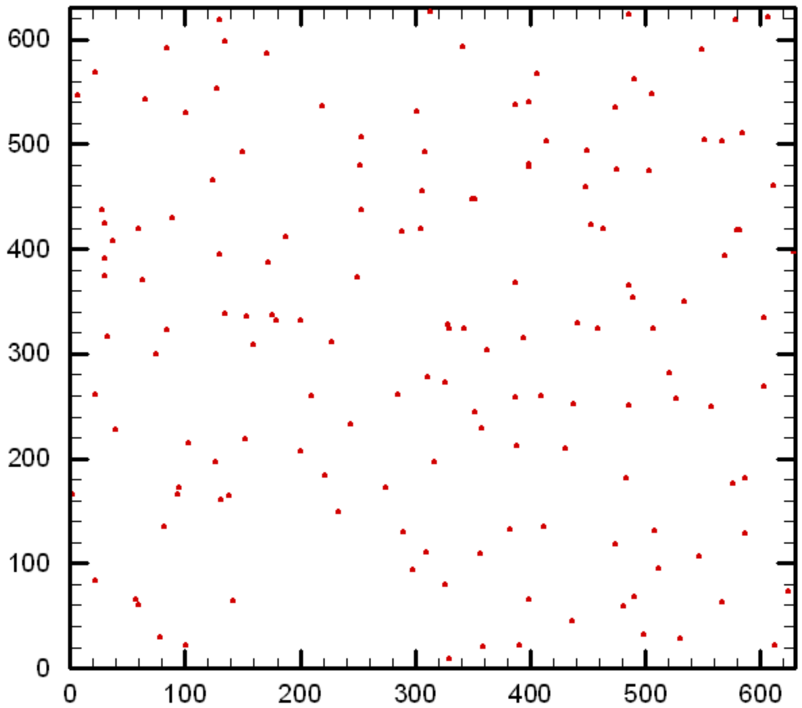
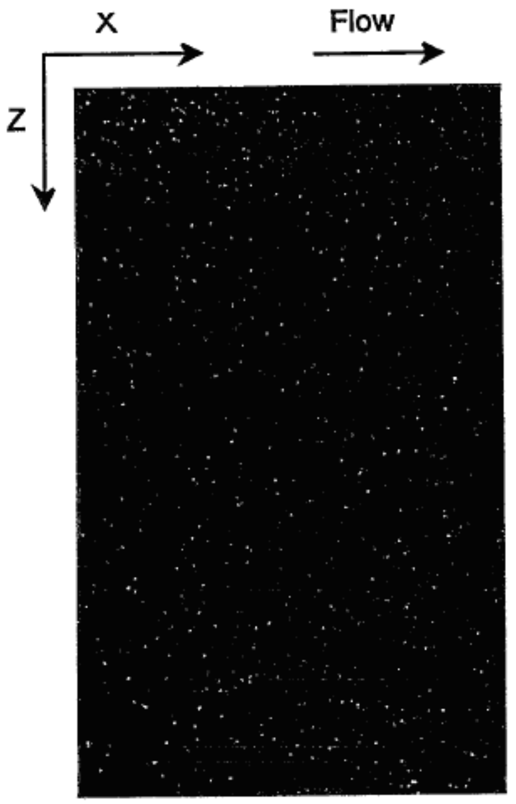


Fessler et al. (1994)



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

Particle Distribution

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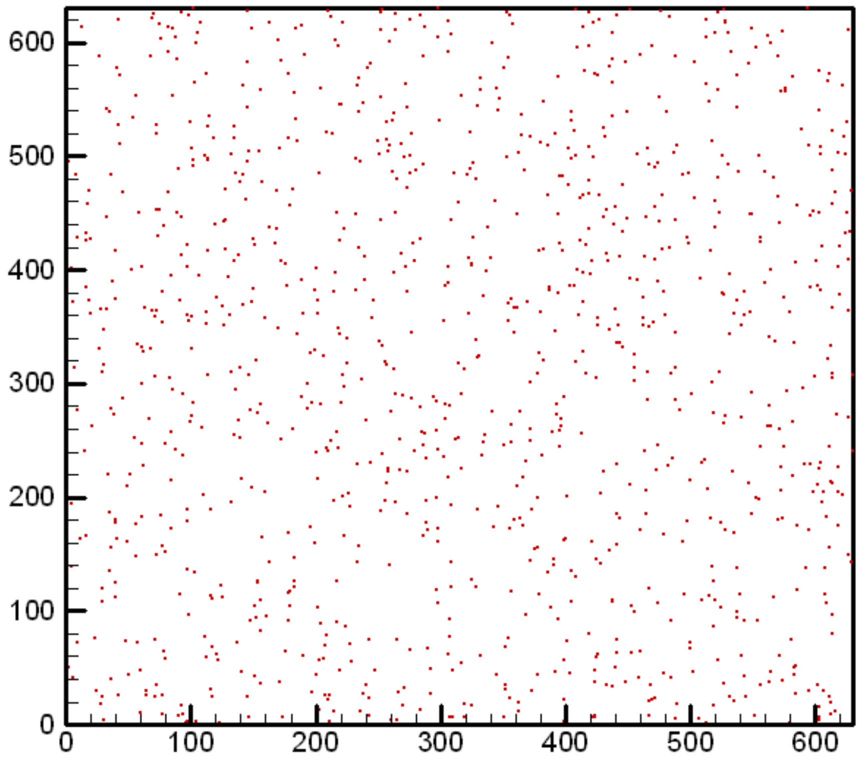
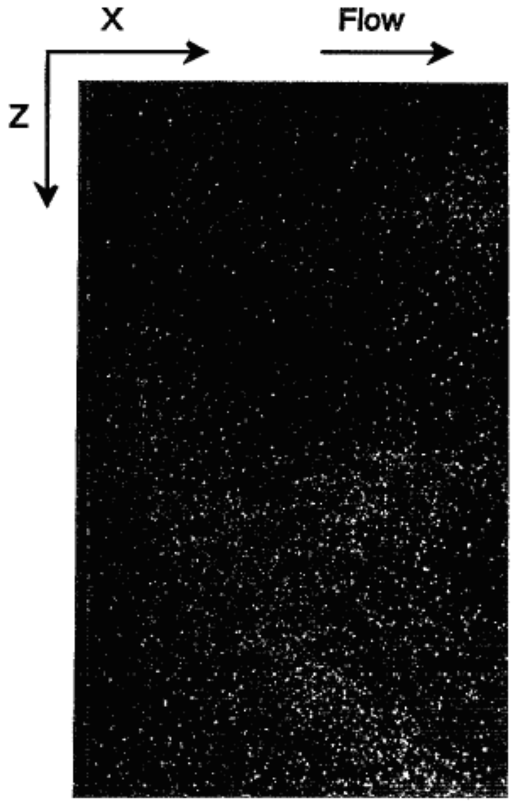


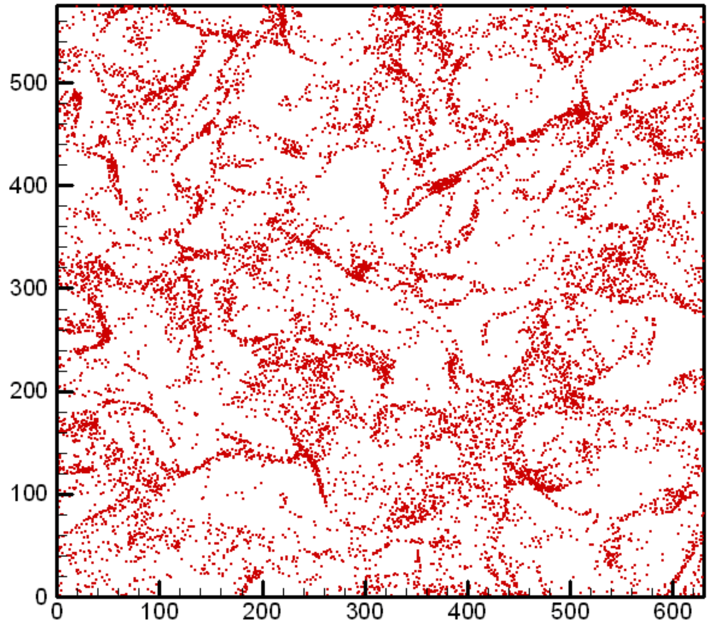
Fessler et al. (1994)



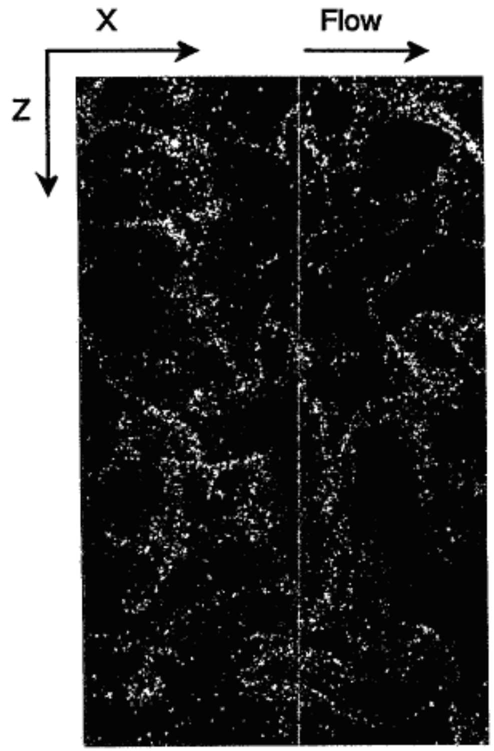
Distribution of 50 micron glass particles (S=2030) at the channel center-plane

Particle Distribution

Clarkson University



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 Stokes number**
- **Inter-particle collisions**

Particle Distribution at the channel center-plane

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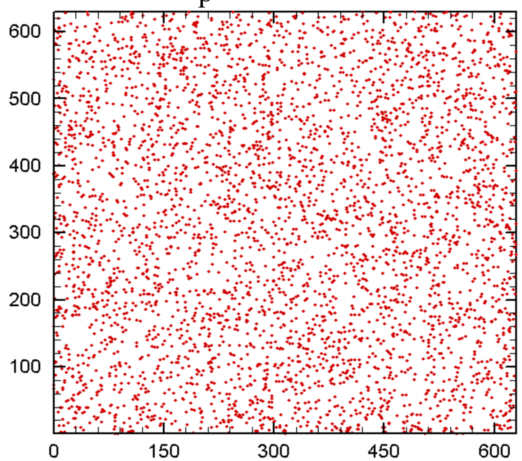
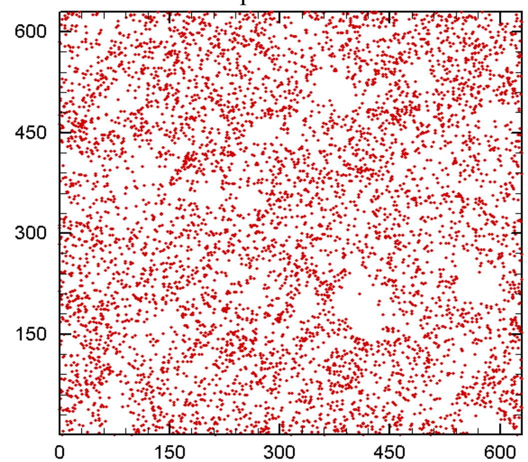
One Way Coupling

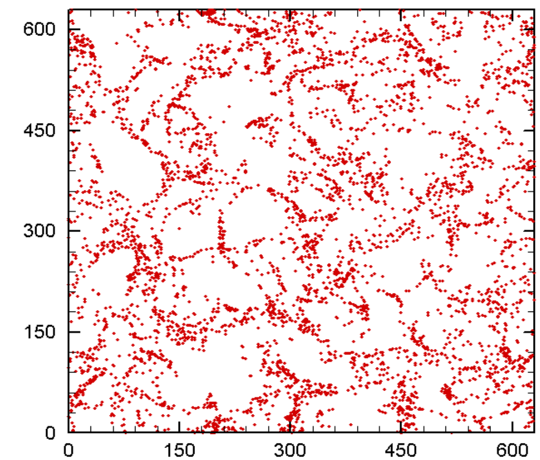
$\tau_p{}^+ = 10^{-4}$



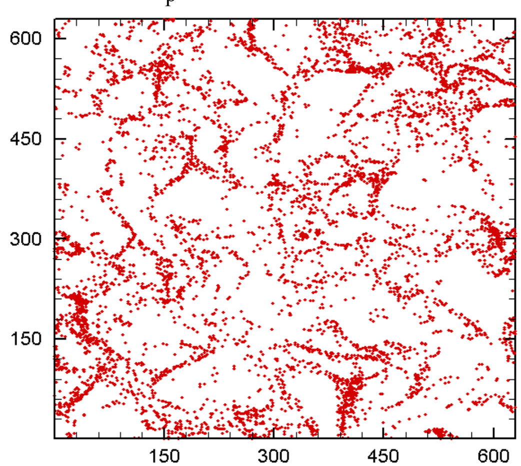
$\tau_p{}^+ = 1.0$



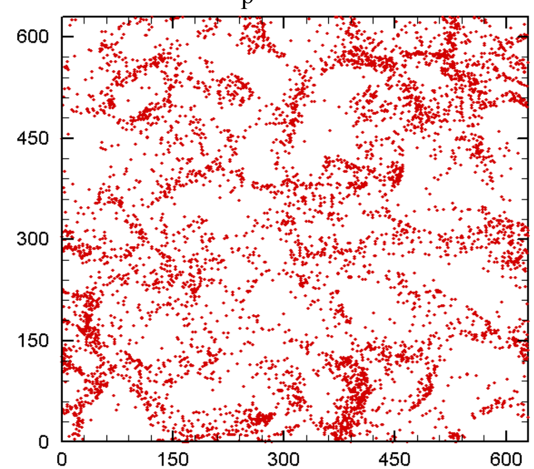
$\tau_p{}^+ = 4.4$



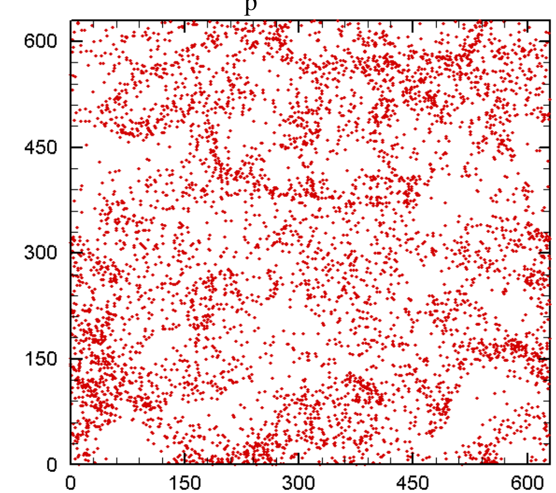
$\tau_p{}^+ = 10.0$



$\tau_p{}^+ = 20$



$\tau_p{}^+ = 40.0$



Particle Distribution and Vorticity Contours

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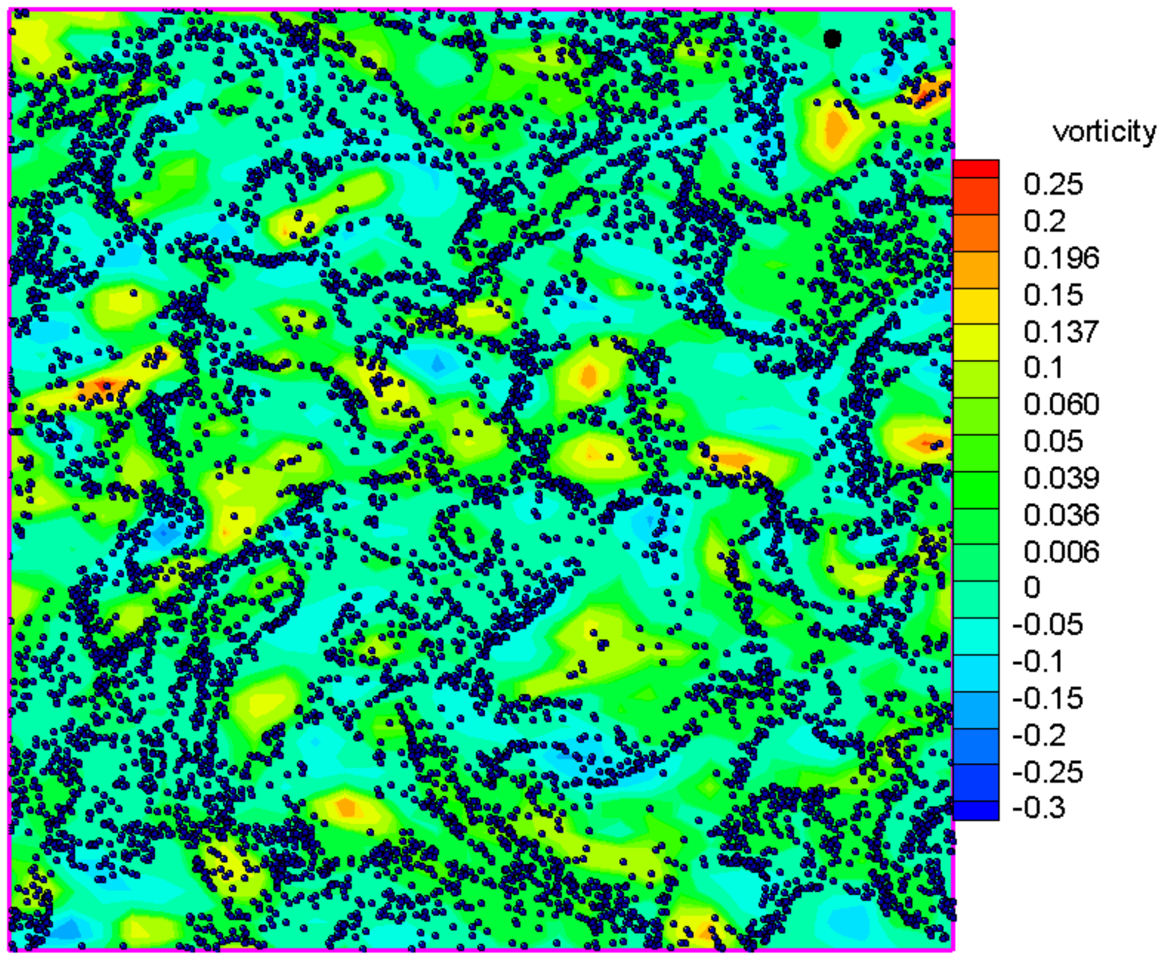
$$\tau_p^+ = 10.0$$

Channel Center Plane



Particle Distribution at Channel Center-Plane

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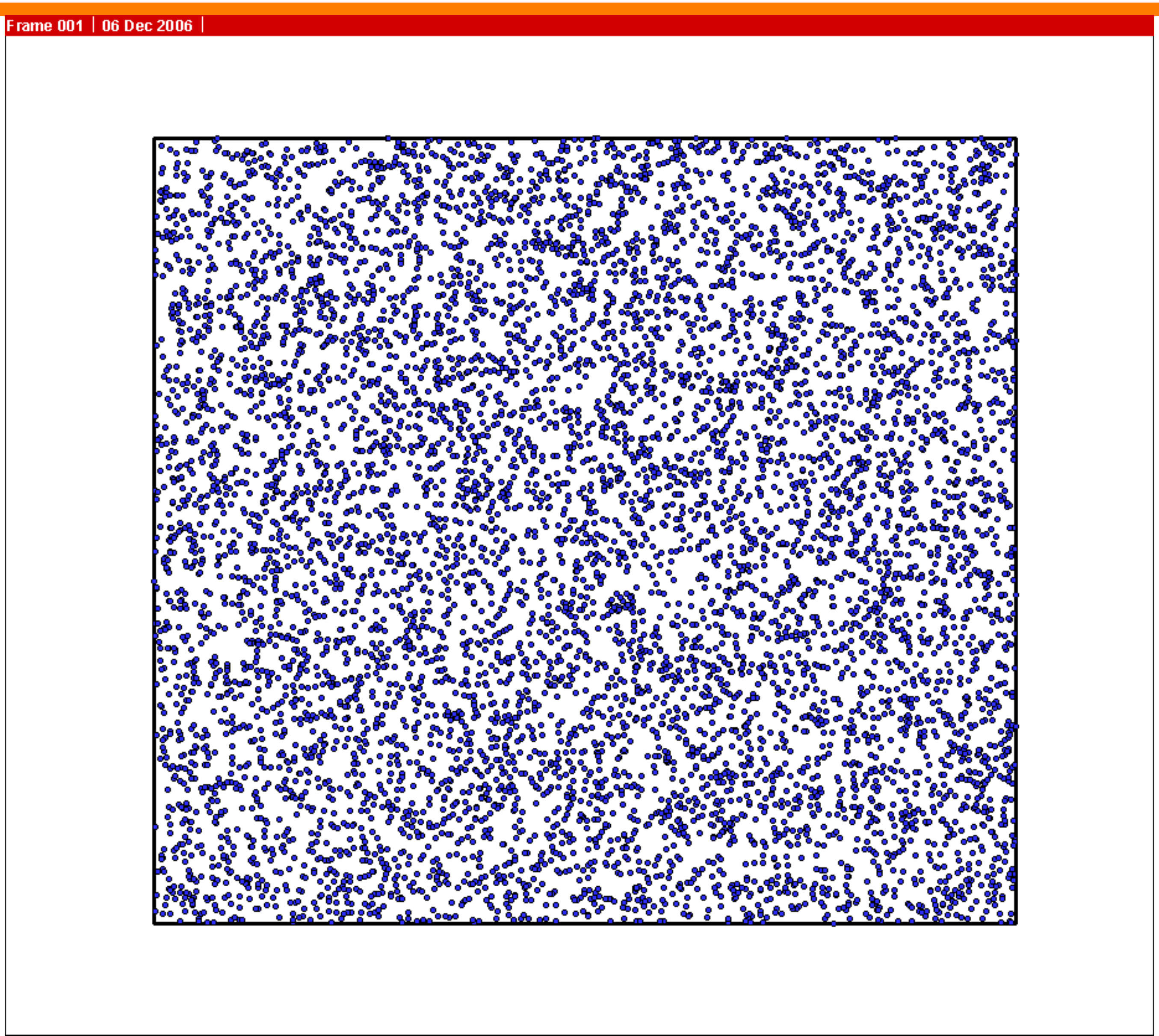
$\tau_p^+ = 10.0$



Particle Distribution in the Wall Region

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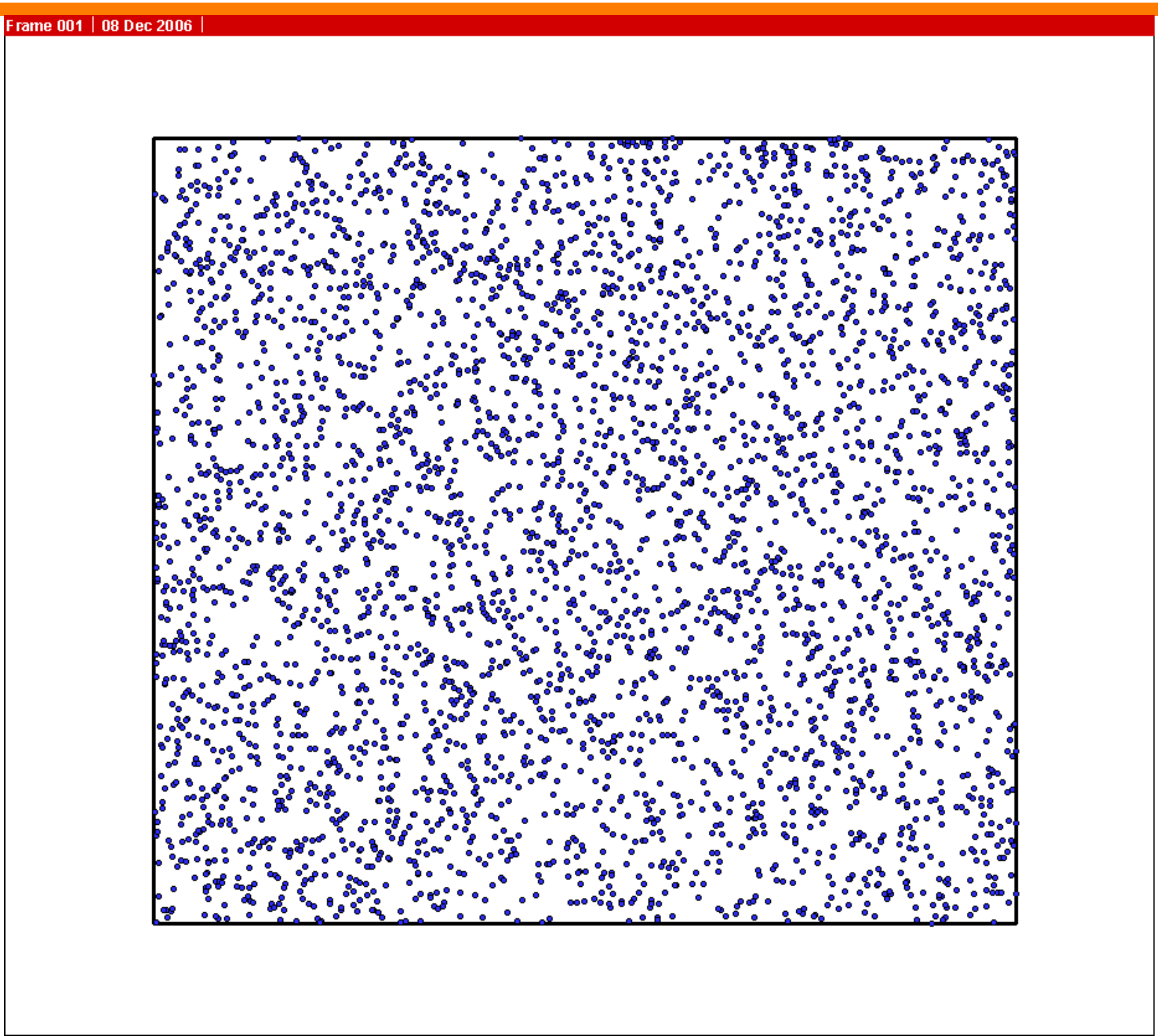
$\tau_p^+ = 10.0$



Numerber of Deposited Particles Versus Time

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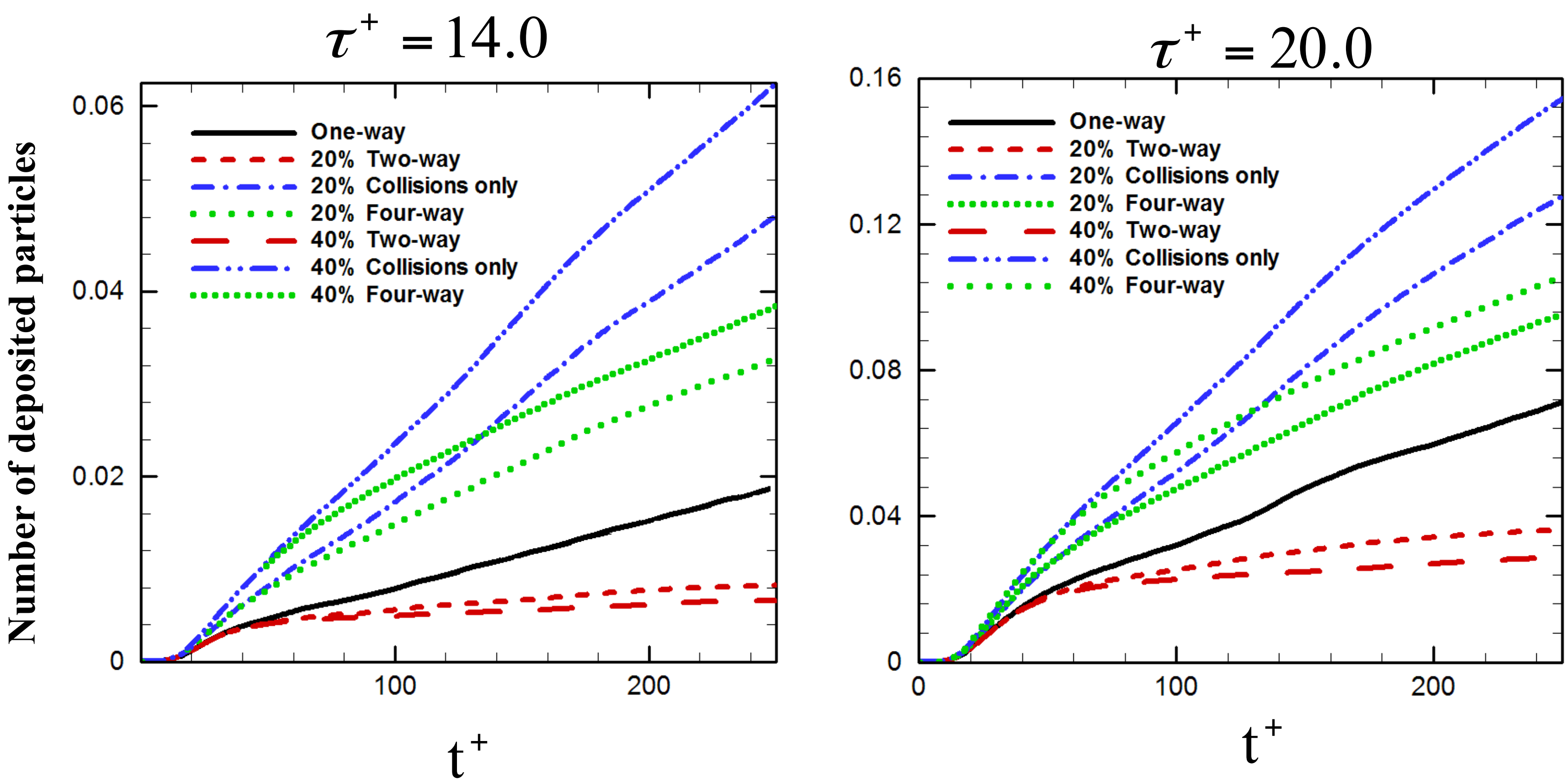
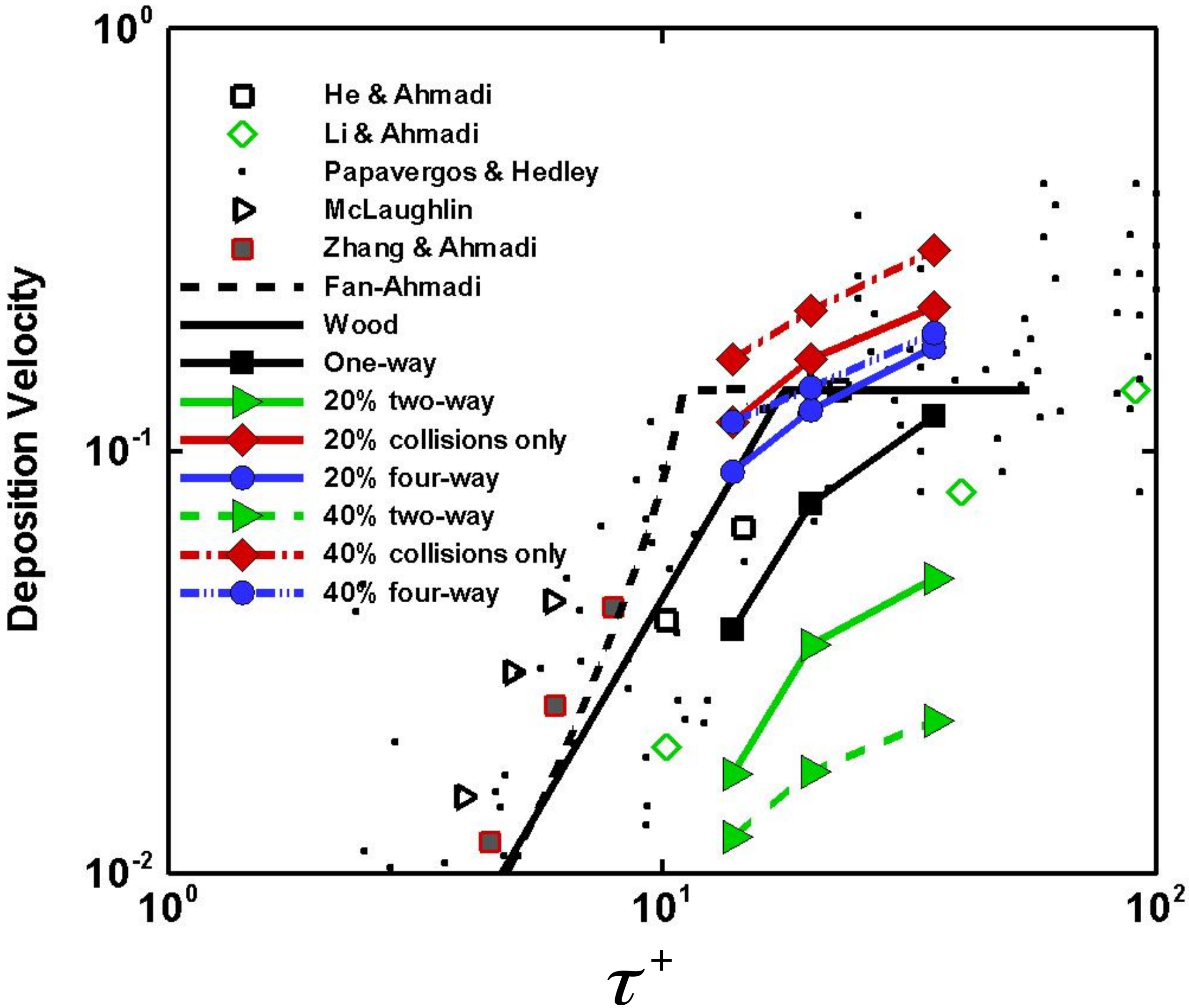
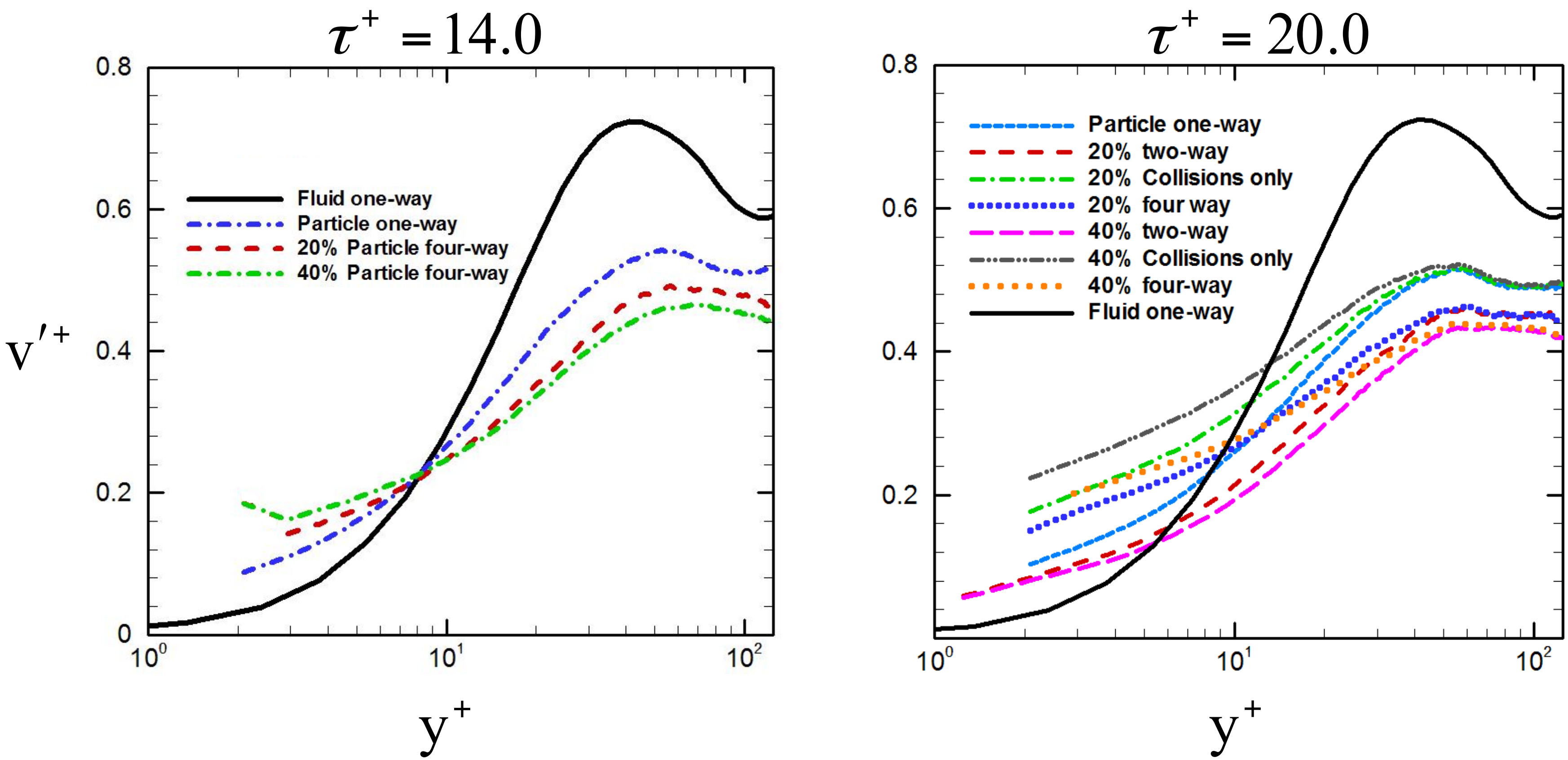


Particle Deposition Velocity



Particle Normal Fluctuating Velocity



Particle Spanwise Fluctuating Velocity

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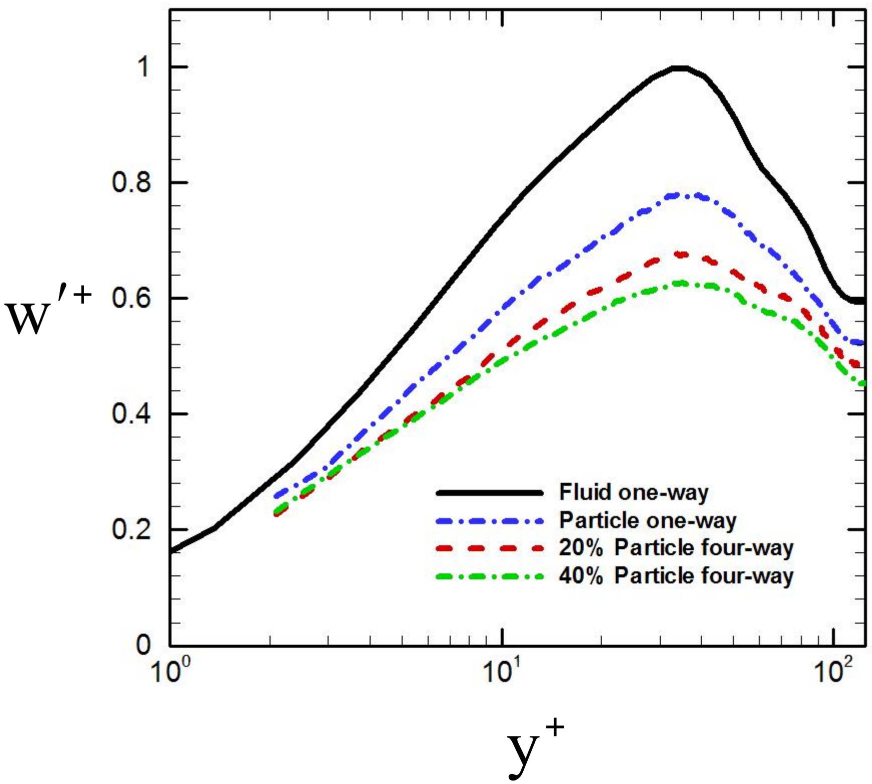
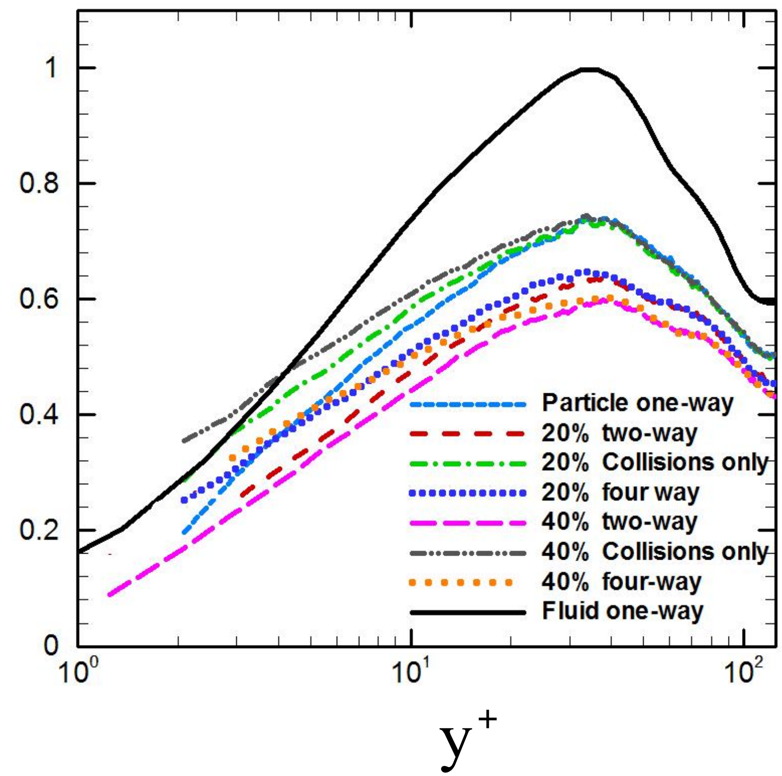
$\tau^+ = 14.0$



$\tau^+ = 20.0$



Particle Streamwise Fluctuating Velocity

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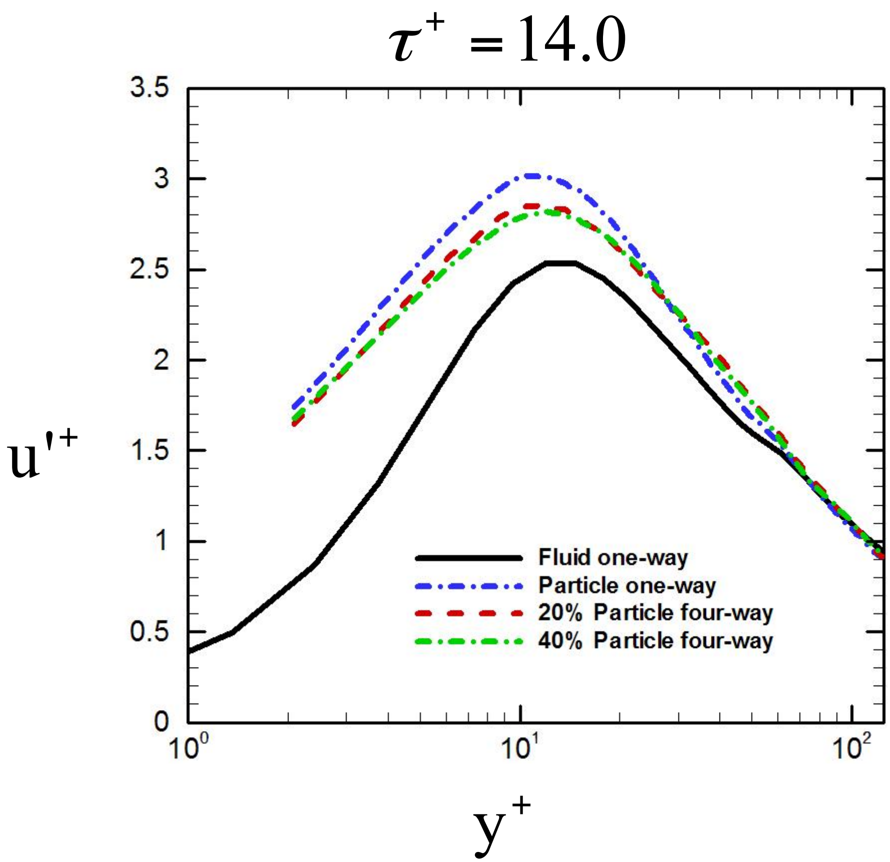

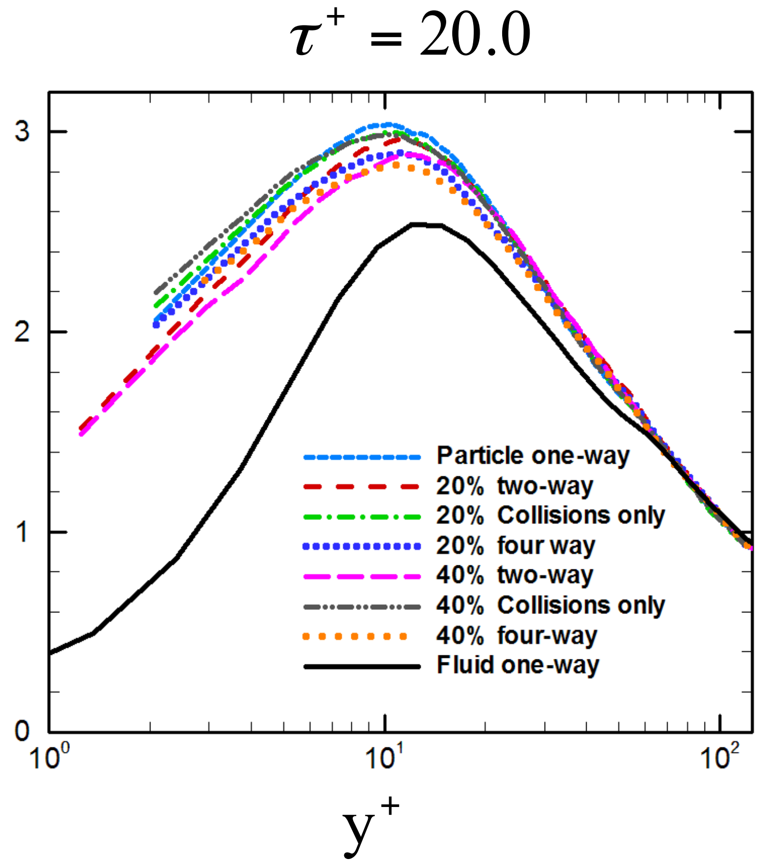

Particle Mean Normal Velocity

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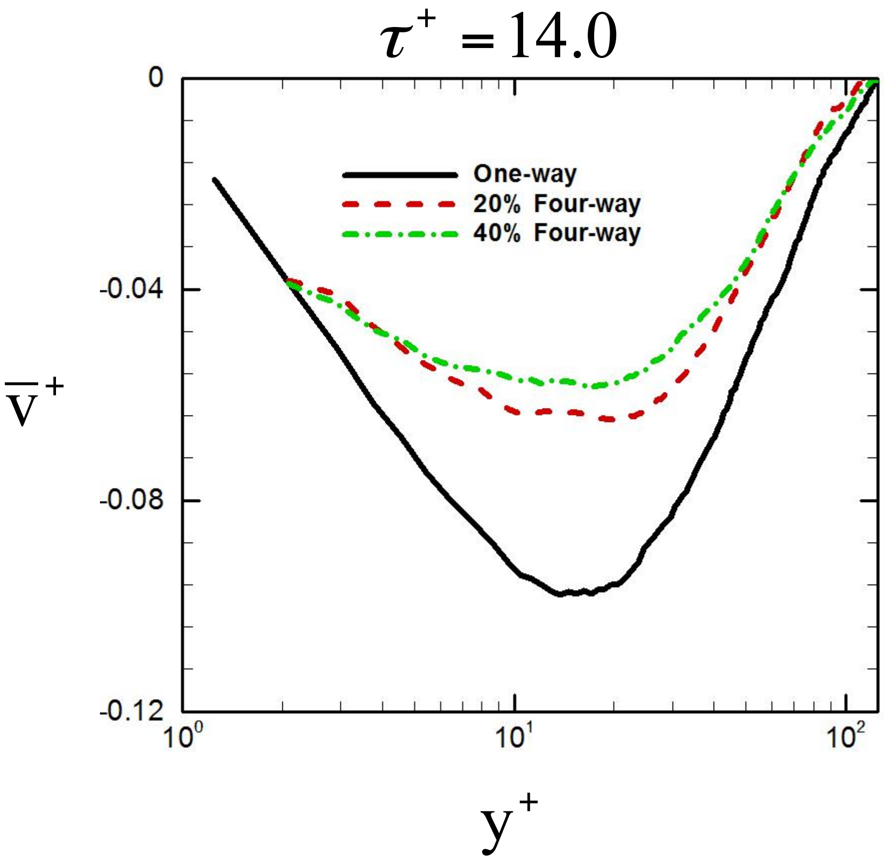

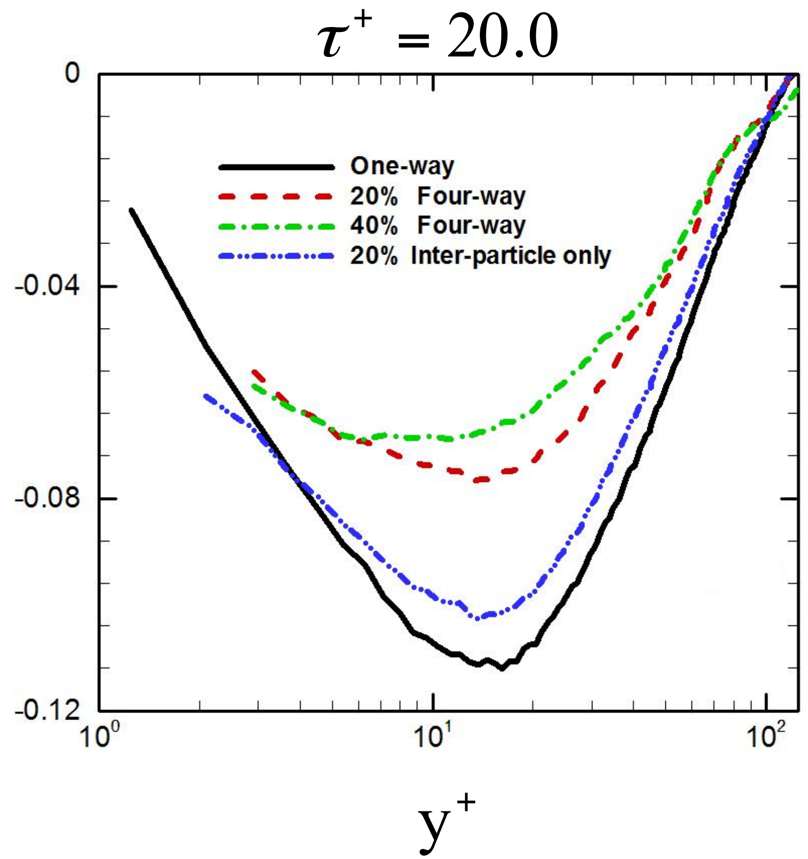

Particle Concentration Profiles

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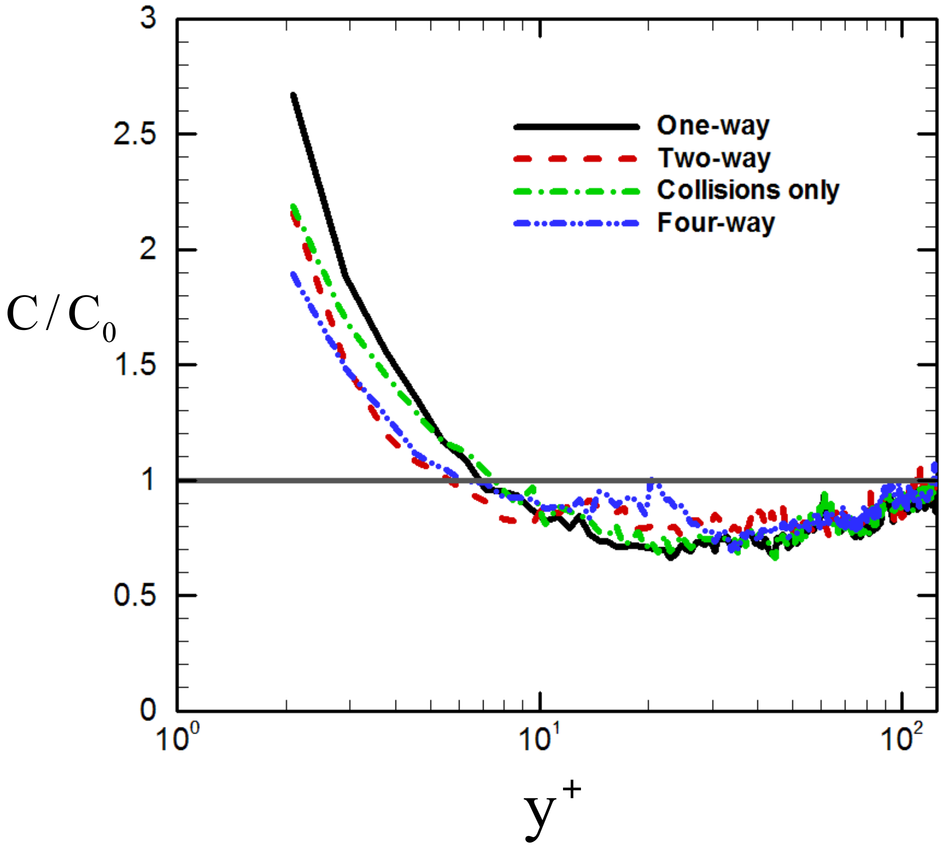
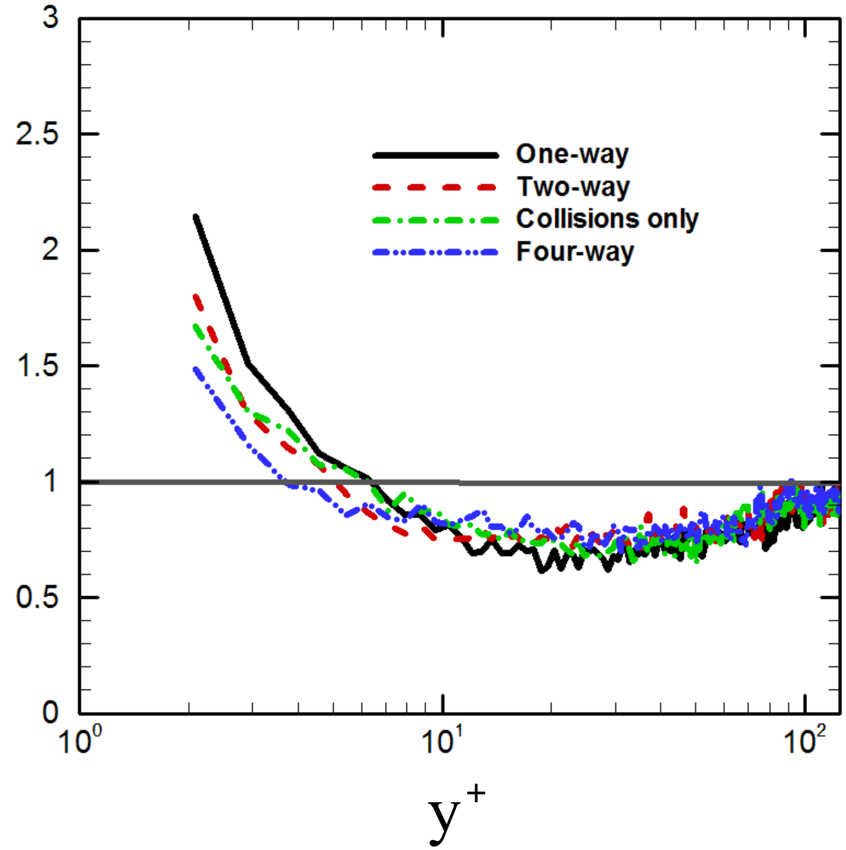
Mass Loading = 20%

$\tau^+ = 14.0$



$\tau^+ = 20.0$

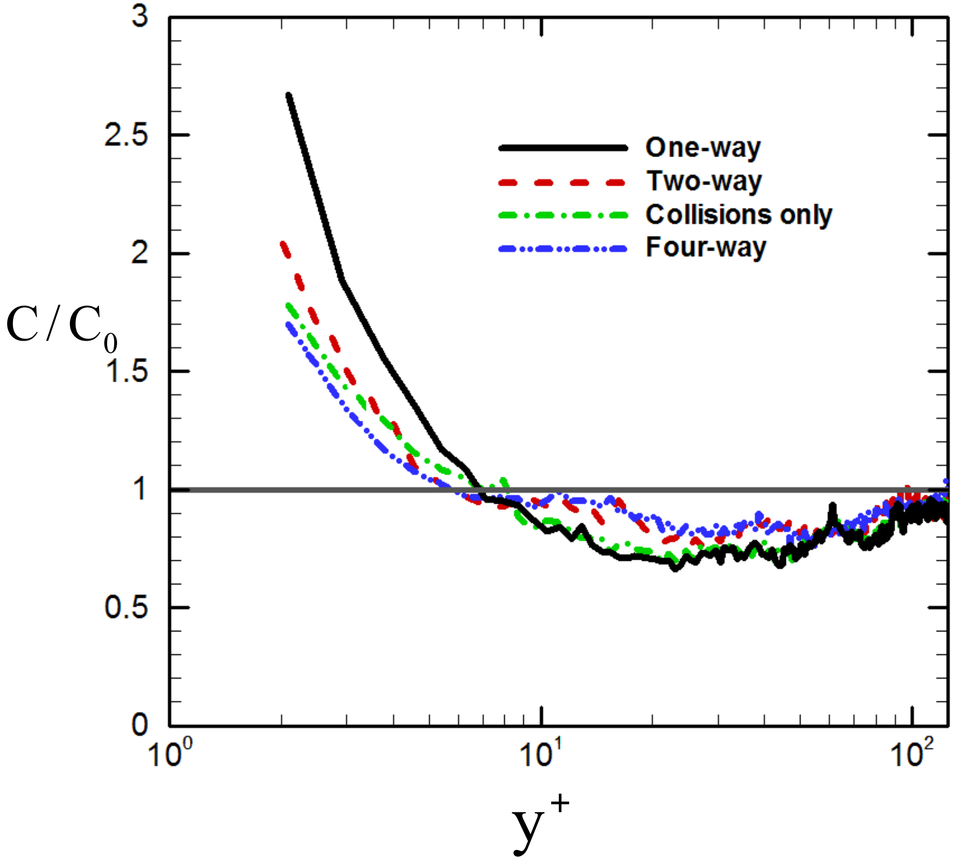


Particle Concentration Profiles

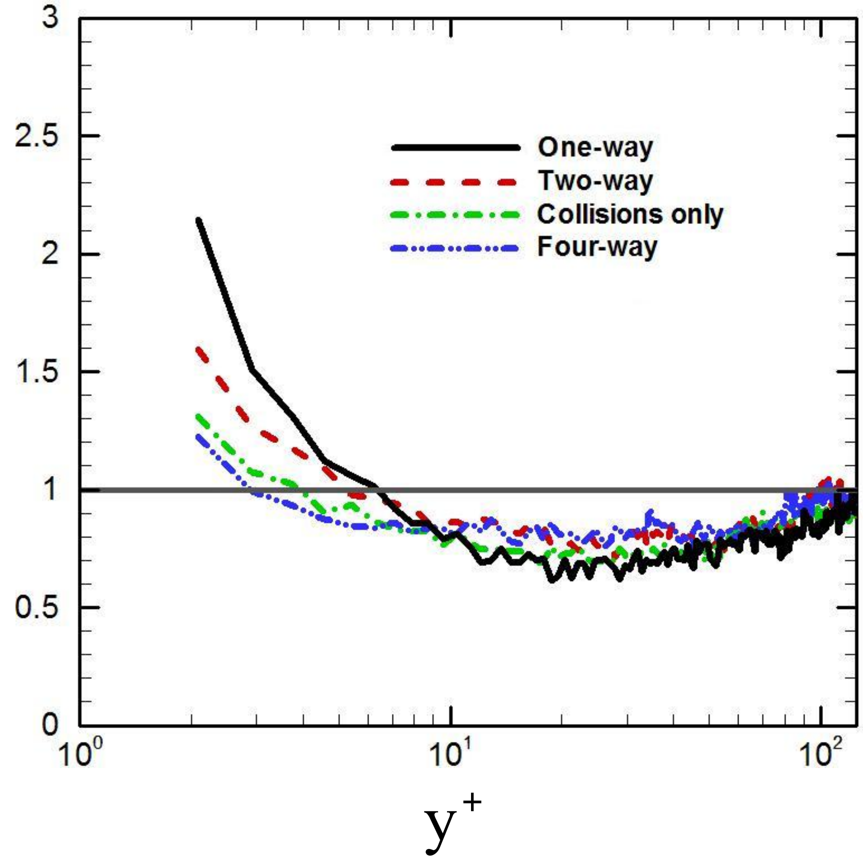
Clarkson University

Mass Loading = 40%

$\tau^+ = 14.0$



$\tau^+ = 20.0$



Fiber Transport and Deposition

Schematics of Ellipsoidal Fiber

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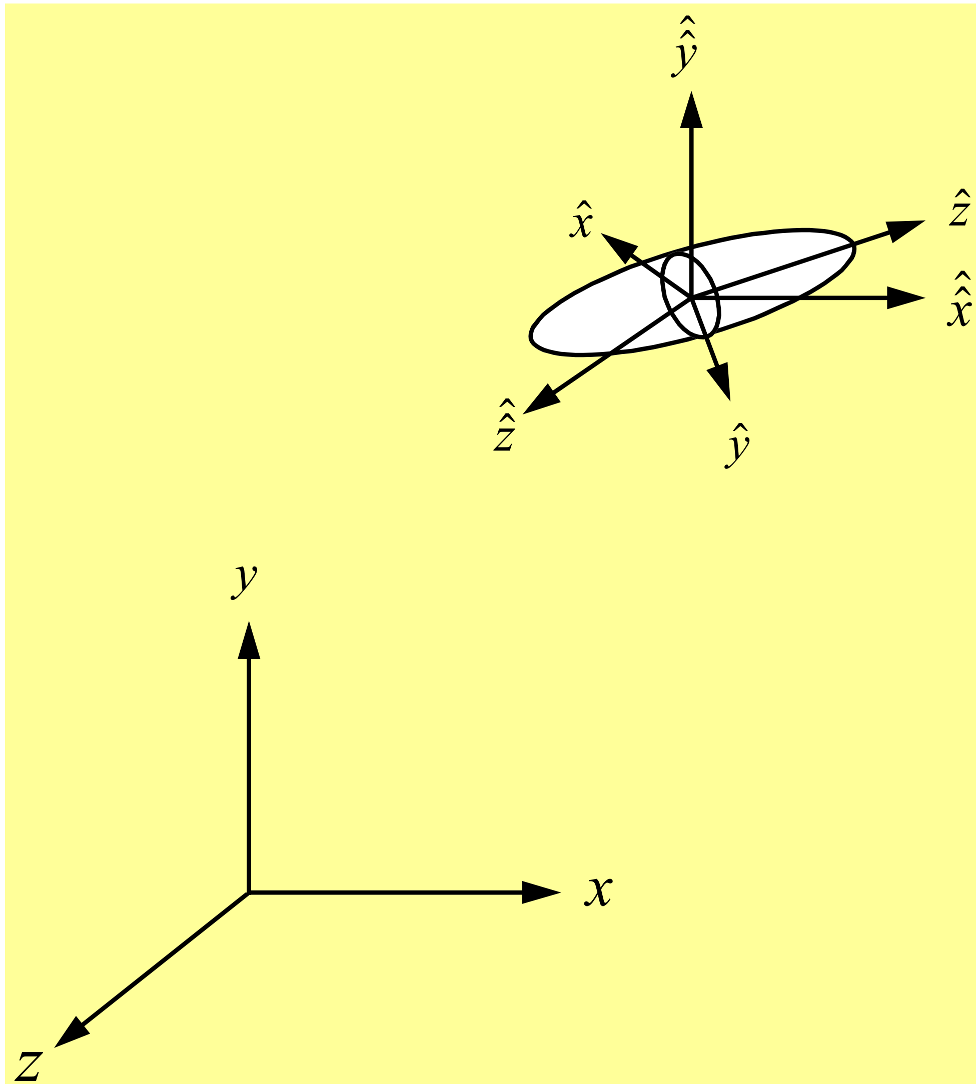

Fiber Equation of Motion

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$$m^p \frac{d\mathbf{v}}{dt} = \left(m^p - m^f\right)\mathbf{g} + \mathbf{f}^h + \mathbf{f}^L$$

$$I_{\hat{x}} \frac{d\omega_{\hat{x}}}{dt} - \omega_{\hat{y}}\omega_{\hat{z}}\left(I_{\hat{y}} - I_{\hat{z}}\right) = T_{\hat{x}}^h$$

$$I_{\hat{y}} \frac{d\omega_{\hat{y}}}{dt} - \omega_{\hat{z}}\omega_{\hat{x}}\left(I_{\hat{z}} - I_{\hat{x}}\right) = T_{\hat{y}}^h$$

$$I_{\hat{z}} \frac{d\omega_{\hat{z}}}{dt} - \omega_{\hat{x}}\omega_{\hat{y}}\left(I_{\hat{x}} - I_{\hat{y}}\right) = T_{\hat{z}}^h$$

Fiber Equation of Motion

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Drag

$$\mathbf{f}^{h} = \mu\pi a \hat{\hat{\mathbf{K}}} \cdot (\mathbf{u} - \mathbf{v})$$

$$\hat{\hat{\mathbf{K}}} = \mathbf{A}^{-1}\hat{\mathbf{K}}\mathbf{A}$$

Shear Lift

$$\mathbf{f}^{L} = \frac{\pi^2 \mu a^2}{\nu^{1/2}} \frac{\partial u_x / \partial y}{\left|\partial u_x / \partial y\right|^{1/2}} \left(\hat{\hat{\mathbf{K}}} \cdot \mathbf{L} \cdot \hat{\hat{\mathbf{K}}}\right) \cdot (\mathbf{u} - \mathbf{v})$$

$$k_{\hat{x}\hat{x}} = k_{\hat{y}\hat{y}} = \frac{16(\beta^2 - 1)}{\left[(2\beta^2 - 3)\ln\left(\beta + \sqrt{\beta^2 - 1}\right) / \sqrt{\beta^2 - 1}\right] + \beta}$$

$$k_{\hat{z}\hat{z}} = \frac{8(\beta^2 - 1)}{\left[(2\beta^2 - 1)\ln\left(\beta + \sqrt{\beta^2 - 1}\right) / \sqrt{\beta^2 - 1}\right] - \beta}$$

Equivalent Relaxation Time Shapiro-Goldenberg

$$\tau^{+}_{eq} = \frac{4\beta S a^{+2}}{9}\left(\frac{1}{k_{\hat{x}\hat{x}}} + \frac{1}{k_{\hat{y}\hat{y}}} + \frac{1}{k_{\hat{z}\hat{z}}}\right) = \frac{2\beta S a^{+2}}{9} \frac{\ln\left(\beta + \sqrt{\beta^2 - 1}\right)}{\sqrt{\beta^2 - 1}}$$

Fiber Equation of Motion

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Equivalent Relaxation Time (Fan-Ahmadi)

$$\tau_{eq}^{+} = \frac{4\beta S a^{+2}}{k_{\hat{x}\hat{x}} + k_{\hat{y}\hat{y}} + k_{\hat{z}\hat{z}}}$$

Hydrodynamic Torque

$$T_{\hat{x}}^{h} = \frac{16\pi\mu a^{3}\beta}{3\left(\beta_0 + \beta^2\gamma_0\right)}\left[\left(1-\beta^2\right)d_{\hat{z}\hat{y}} + \left(1+\beta^2\right)\left(w_{\hat{z}\hat{y}} - \omega_{\hat{x}}\right)\right]$$

$$T_{\hat{y}}^{h} = \frac{16\pi\mu a^{3}\beta}{3\left(\alpha_0 + \beta^2\gamma_0\right)}\left[\left(\beta^2-1\right)d_{\hat{x}\hat{z}} + \left(1+\beta^2\right)\left(w_{\hat{x}\hat{z}} - \omega_{\hat{y}}\right)\right]$$

$$T_{\hat{z}}^{h} = \frac{32\pi\mu a^{3}\beta}{3\left(\alpha_0 + \beta_0\right)}\left(w_{\hat{y}\hat{z}} - \omega_{\hat{z}}\right)$$

Sample Fiber Trajectories

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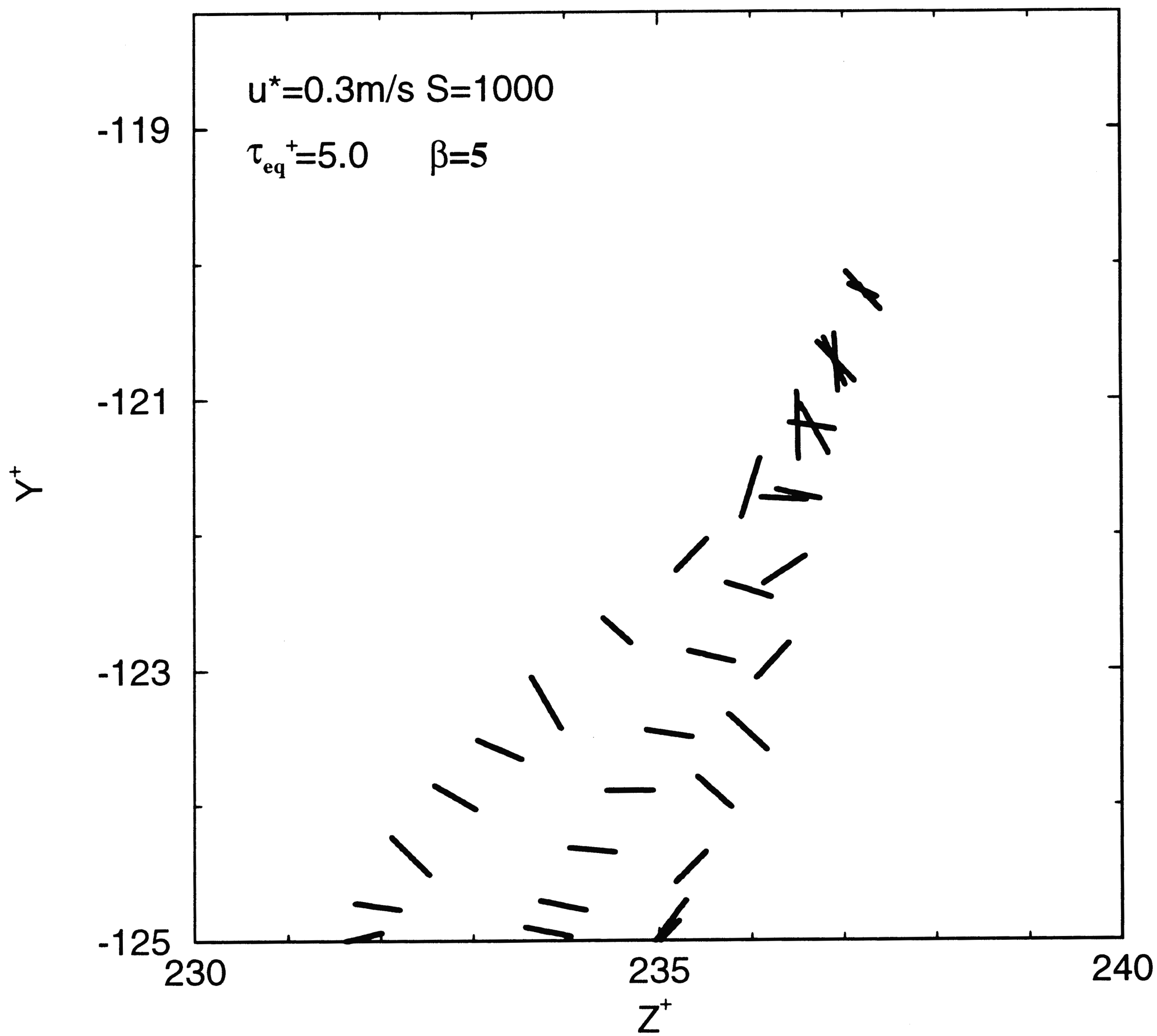
Effects of Initial Orientation



Sample Fiber Trajectories

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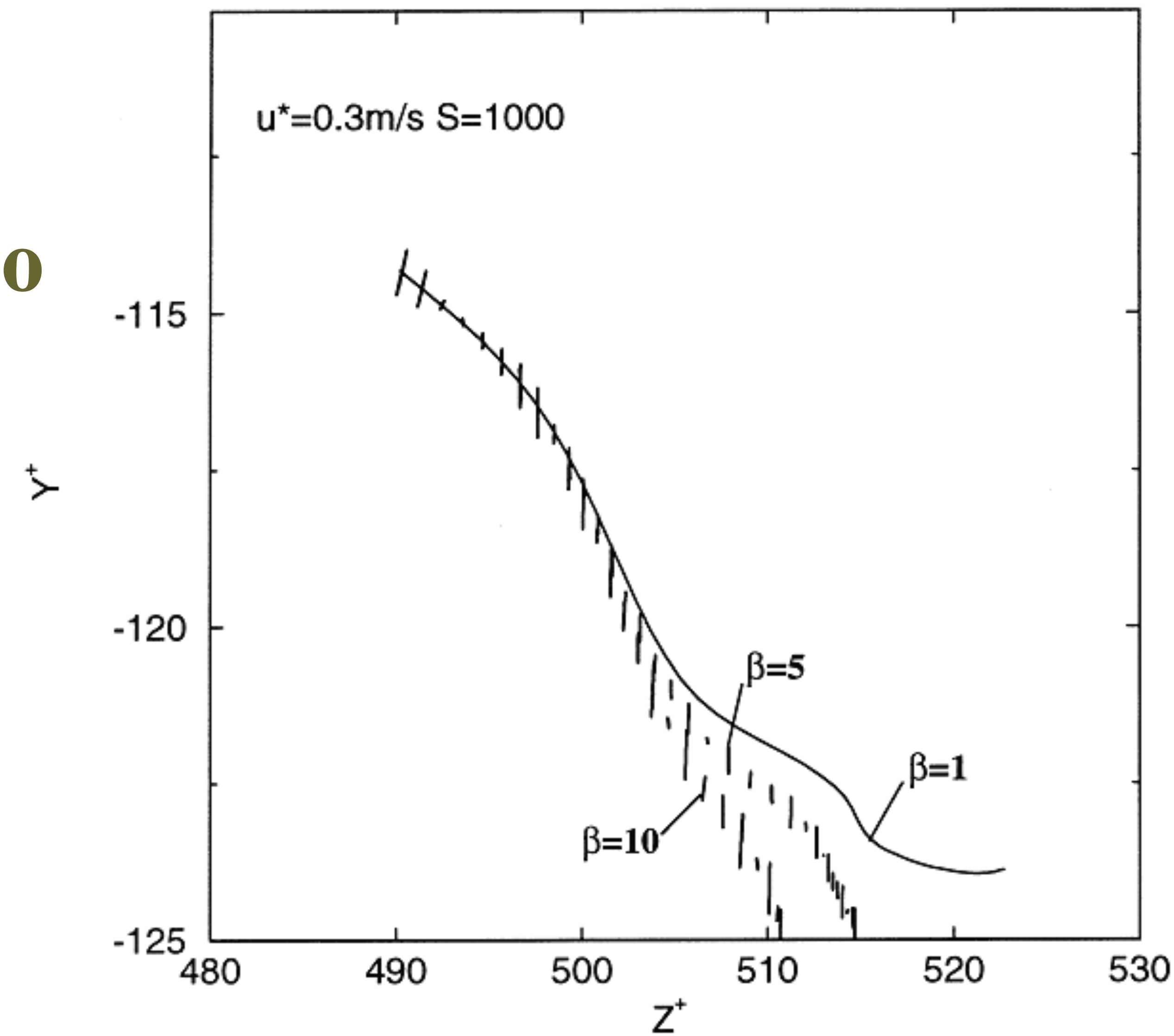
Effects of Aspect Ratio



Fiber Deposition Pattern

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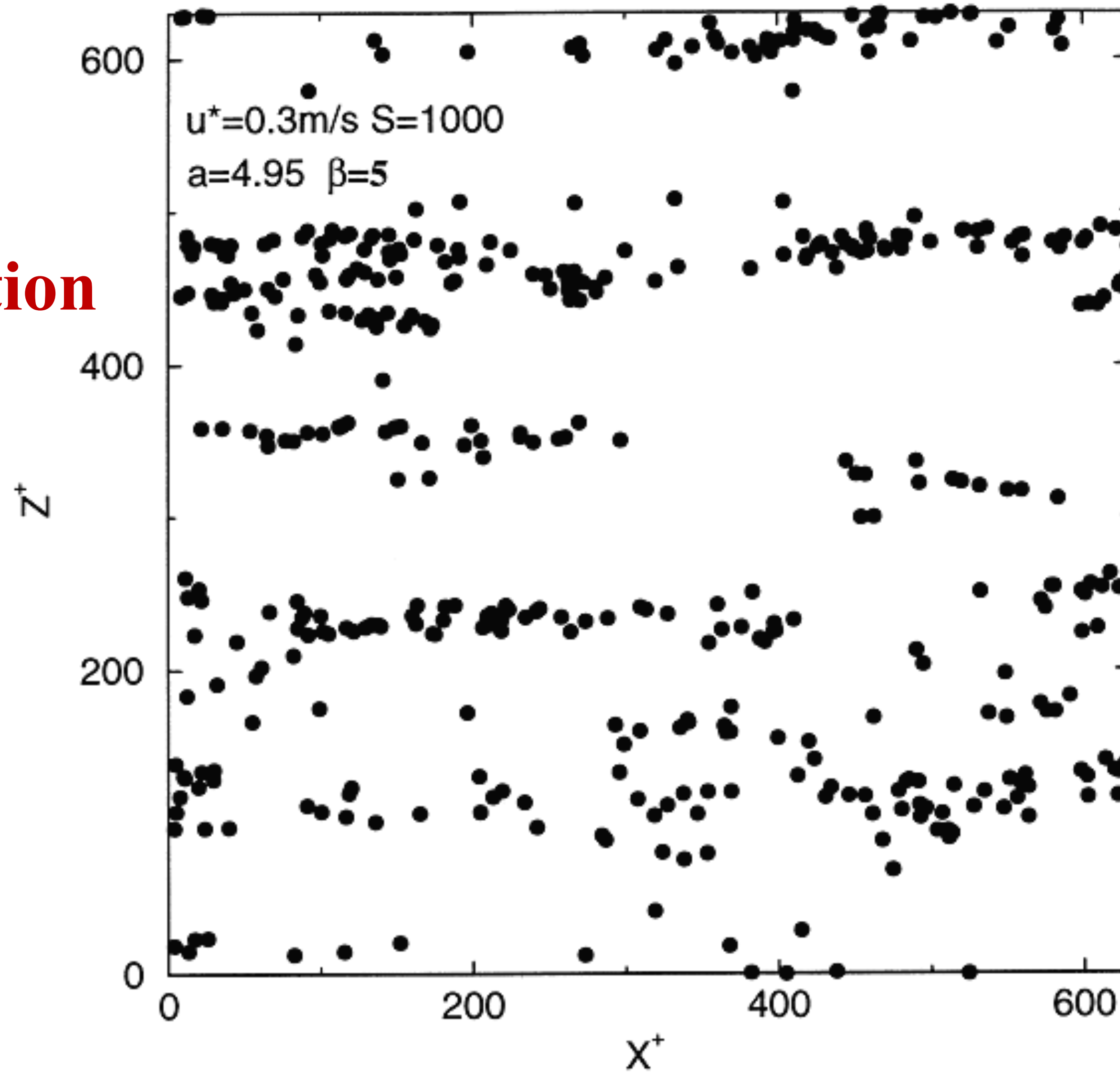
Mean Flow Direction



Fiber Deposition Velocity

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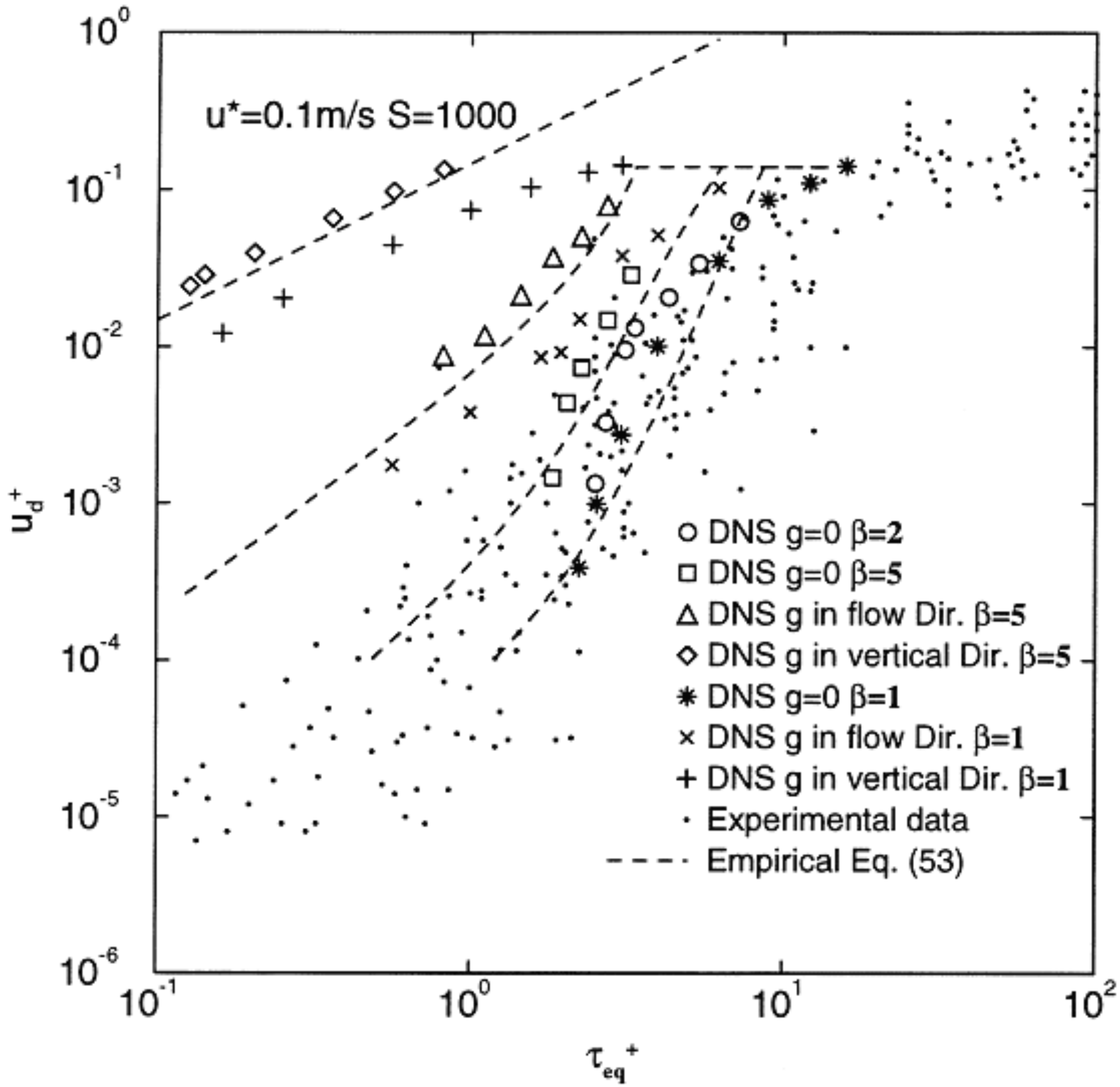

Fiber Deposition Velocity

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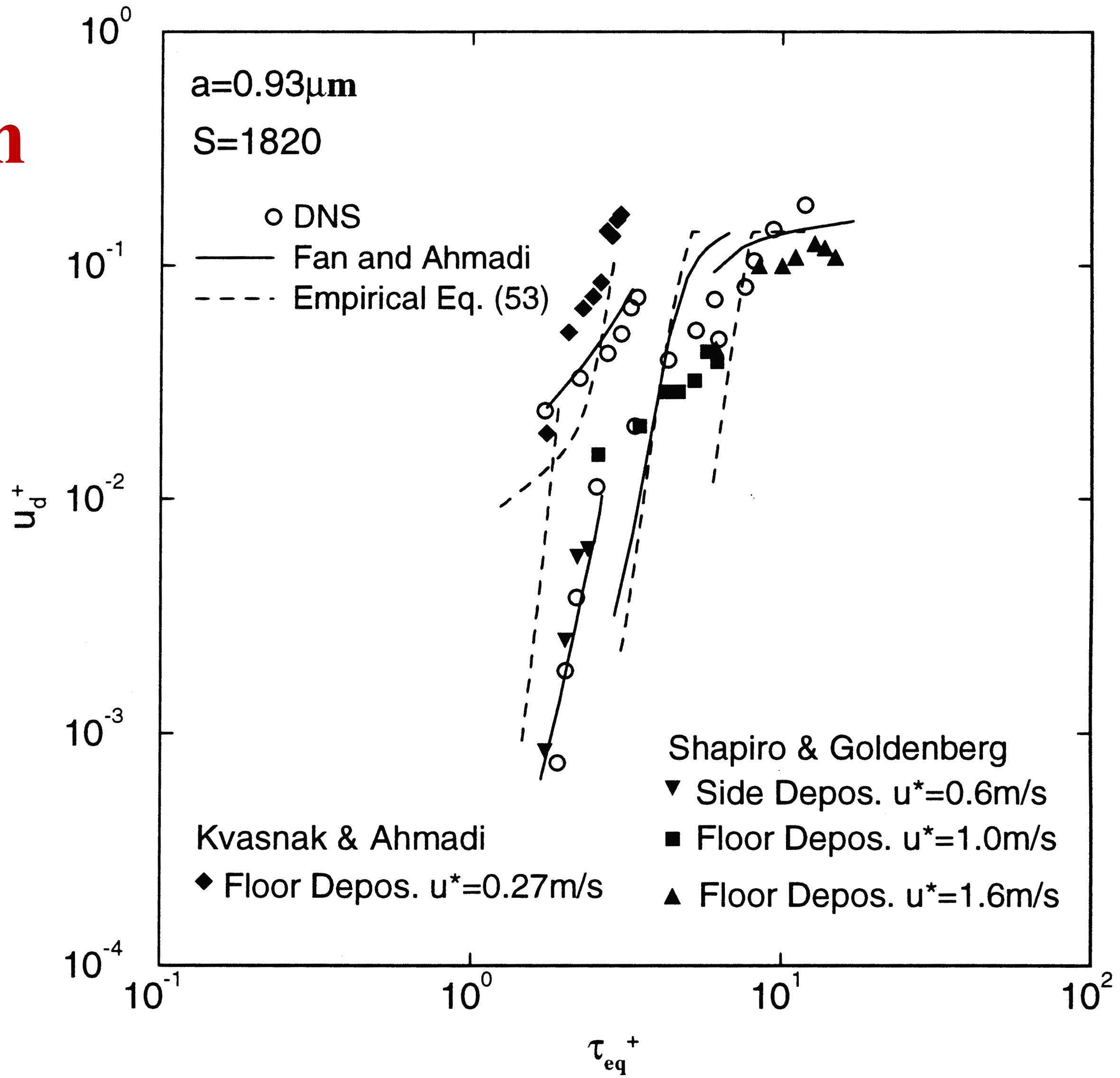
Comparison with Experimental Data



Empirical Equation for Fiber Deposition Velocity

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$$u_d^+ = \begin{cases} 0.0185 \times \left[\dfrac{\dfrac{\beta L^{+2}}{\beta+3} + \dfrac{4\beta \tau_{eq}^{+2} g^+ L_1^+}{0.01085(\beta+3)(1+\tau_{eq}^{+2} L_1^+)}}{3.42 + \dfrac{\tau_{eq}^{+2} g^+ L_1^+}{0.01085(1+\tau_p^{+2} L_1^+)}} \right] \\ \times \left[1 + 8e^{-(\tau_{eq}^+ - 10)^2/32} \right] \dfrac{1}{1 - \tau_{eq}^{+2} L_1^+ \left(1 + \dfrac{g^+}{0.037}\right)} & \text{if } u_d^+ < 0.14 \\ 0.14 & \text{otherwise} \end{cases}$$

$$\mathrm{L}_1^+ = \frac{3.08}{\mathrm{S}d_{eq}^+} = \frac{0.725}{\sqrt{\mathrm{S}\tau_{eq}^+}}$$

$$d_{eq}^+ = \sqrt{\frac{18\tau_{eq}^+}{\mathrm{S}}}$$

Angular Fiber

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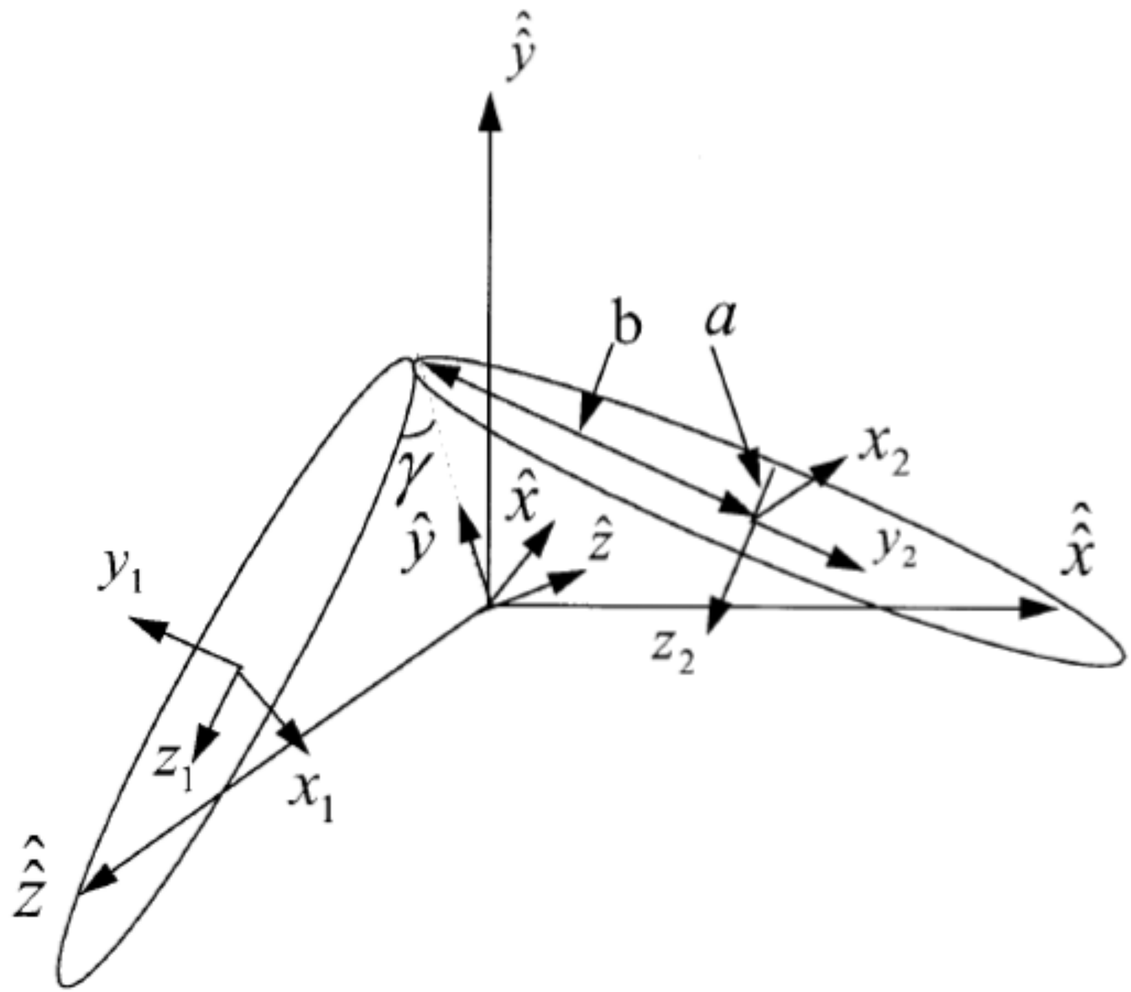

Angular Fiber Parameters

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$$\tau_{eq}^{+} = \frac{8\beta S(a^{+})^2}{R_{xx} + R_{yy} + R_{zz}}$$

$$\mathbf{R} = \mathbf{A}_1^{-1}\mathbf{K}_1\mathbf{A}_1 + \mathbf{A}_2^{-1}\mathbf{K}_2\mathbf{A}_2$$

$$\mathbf{x}_1 = \begin{pmatrix} 0 \\ 0 \\ -b\sin(\gamma) \end{pmatrix} + \mathbf{A}_1\hat{\mathbf{x}}$$

$$\mathbf{A}_1 = \begin{bmatrix} -1 & 0 & 0 \\ 0 & \sin\gamma & -\cos\gamma \\ 0 & -\cos\gamma & -\sin\gamma \end{bmatrix}$$

$$\mathbf{x}_2 = \begin{pmatrix} 0 \\ 0 \\ b\sin(\gamma) \end{pmatrix} + \mathbf{A}_2\hat{\mathbf{x}}$$

$$\mathbf{A}_2 = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -\sin\gamma & -\cos\gamma \\ 0 & -\cos\gamma & \sin\gamma \end{bmatrix}$$

Angular Fiber Sample Trajectories

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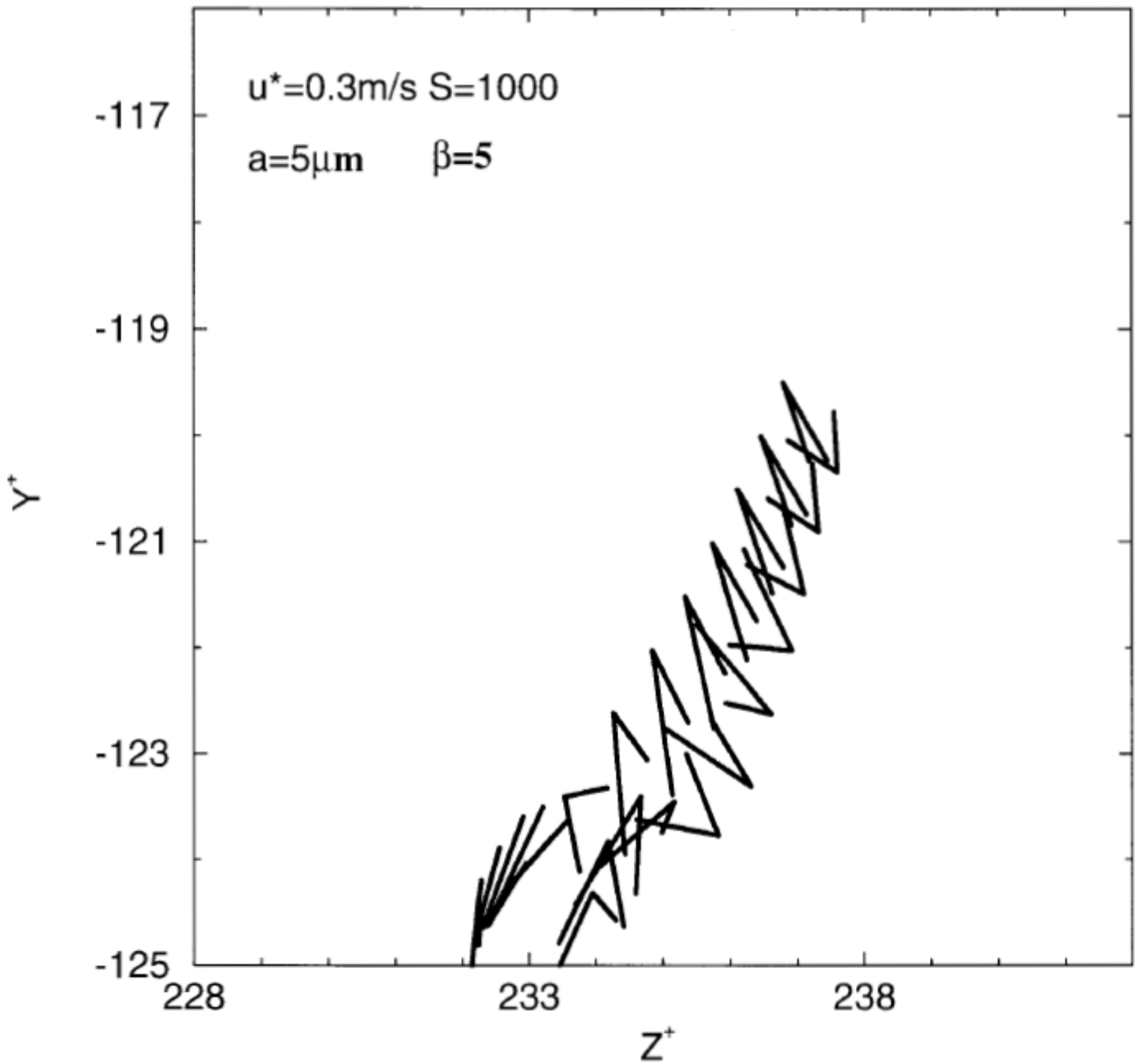

Angular Fiber Sample Trajectories

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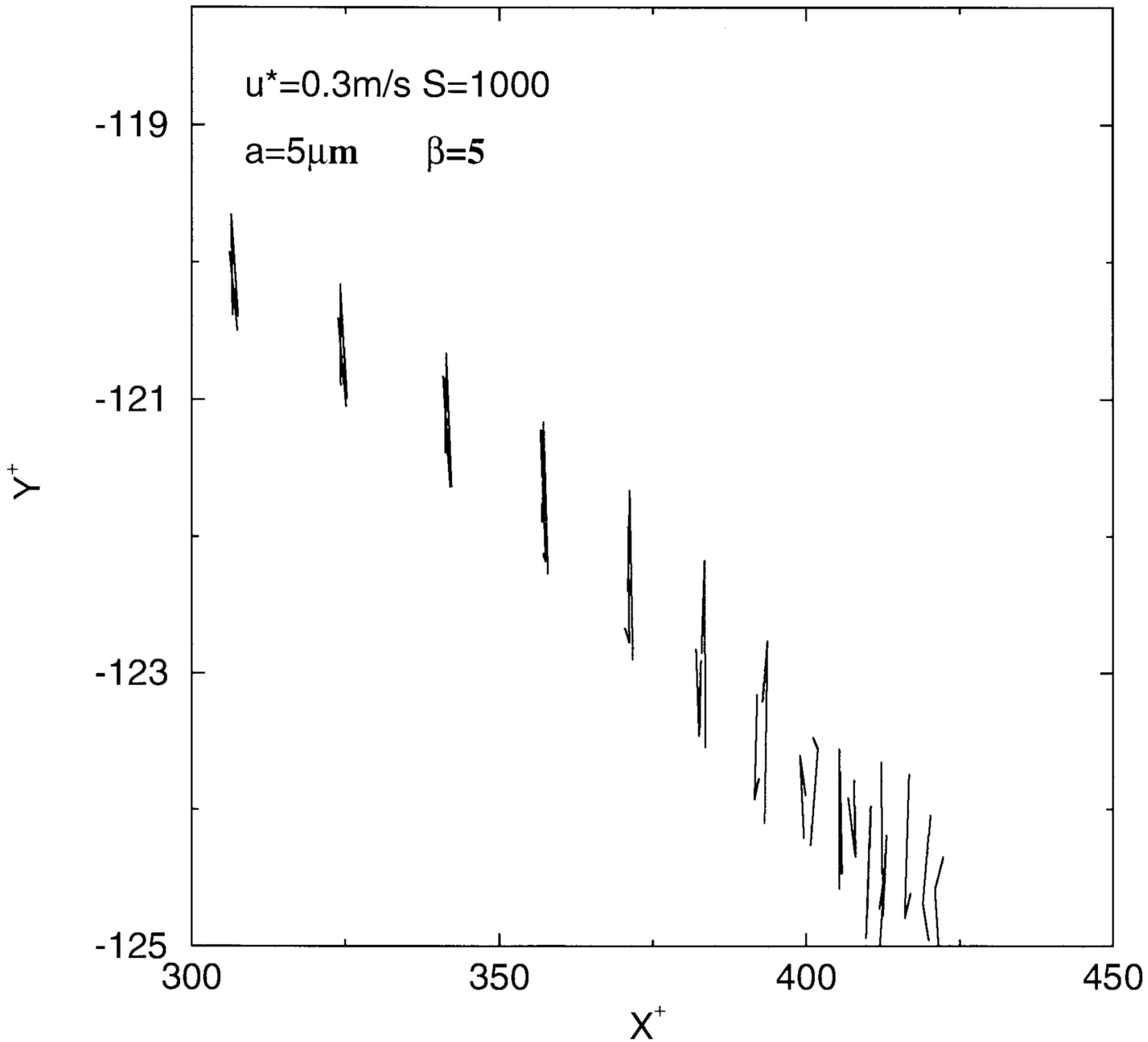

Angular Fiber Deposition Velocity

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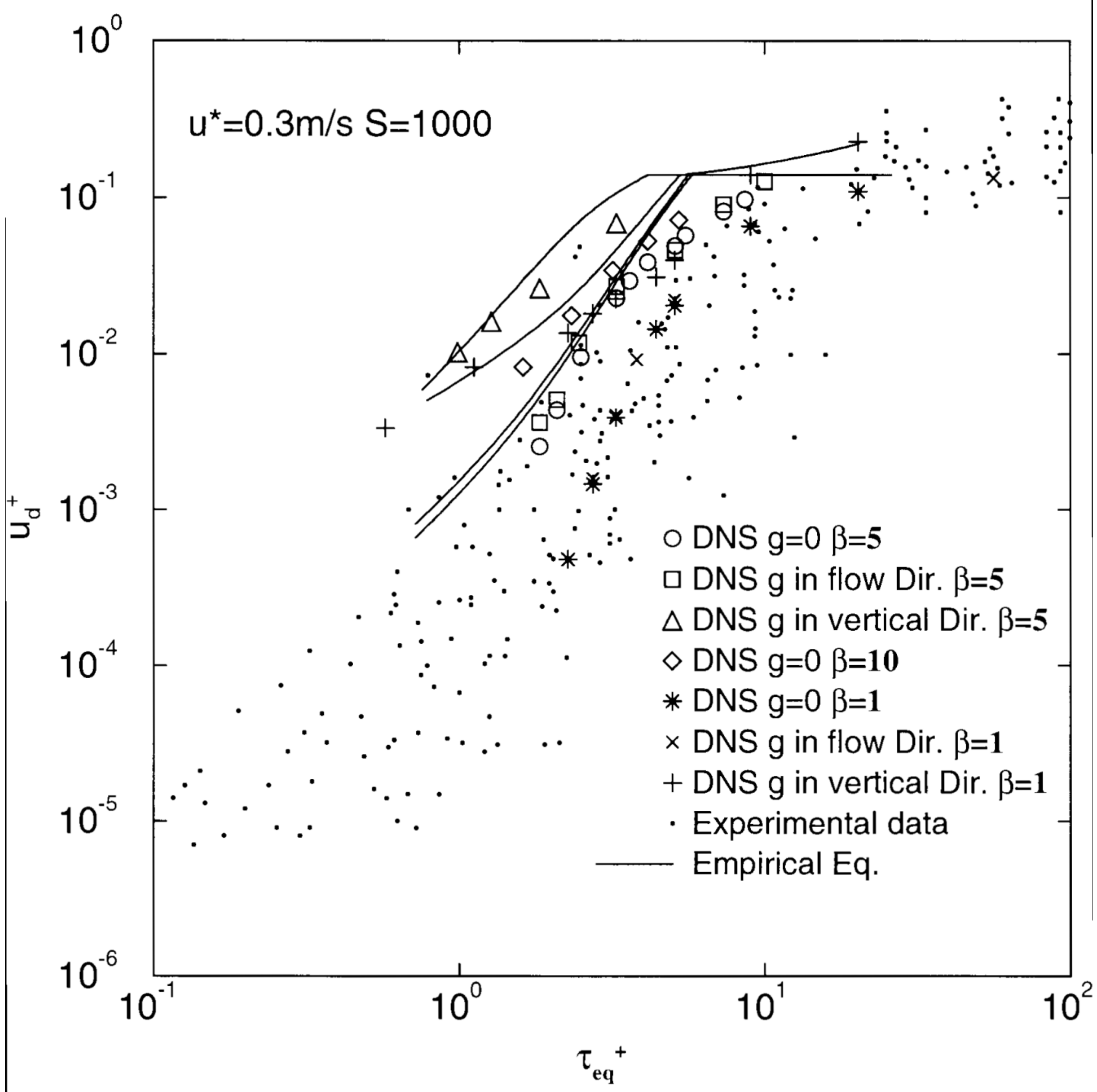

Empirical Equation for Angular Fiber Deposition Velocity

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$$u_d^+ = \begin{cases} 0.0185 \times \left[\dfrac{\dfrac{\beta L^{+2}}{\beta+3} + \dfrac{4\beta\tau_{eq}^{+2} g^+ L_1^+}{0.01085(\beta+3)(1+\tau_{eq}^{+2}L_1^+)}}{3.42 + \dfrac{\tau_{eq}^{+2} g^+ L_1^+}{0.01085(1+\tau_p^{+2}L_1^+)}} \right]^{1/\left(1+\tau_{eq}^{+4\beta/(1+\beta)}L_1^+\right)} & \text{if} \quad u_d^+ < 0.14 \\ \times \left[1 + 8e^{-(\tau_{eq}^+ - 10)^2/32}\right] \dfrac{1}{1 - \tau_{eq}^{+2} L_1^+ (1 + \dfrac{g^+}{0.037})} & \\ 0.14 \qquad \text{otherwise} & \end{cases}$$

$$L_1^+ = \frac{3.08}{S d_{eq}^+} = \frac{0.725}{\sqrt{S\tau_{eq}^+}}$$

$$d_{eq}^+ = \sqrt{\frac{18\tau_{eq}^+}{S}}$$

$$\mathbf{g}^+ = \frac{\nu}{u^{*3}}\mathbf{g}$$

$$L^+ = \begin{cases} 2a^+\beta & \gamma < \dfrac{\pi}{6} \\ 4a^+\beta \sin\gamma & \gamma \geq \dfrac{\pi}{6} \end{cases}$$

Angular Fiber Deposition Velocity

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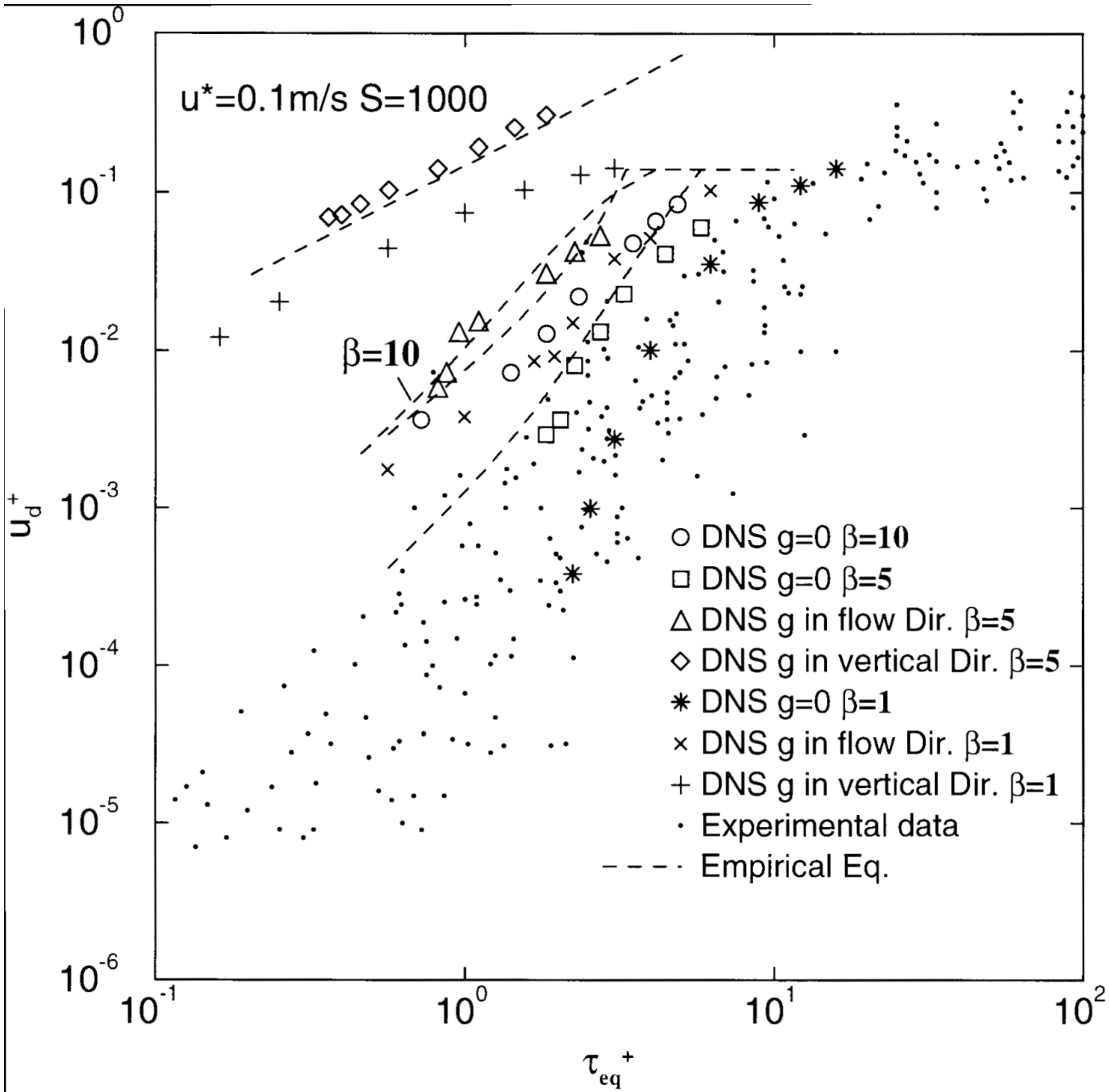

Angular Fiber Deposition Velocity

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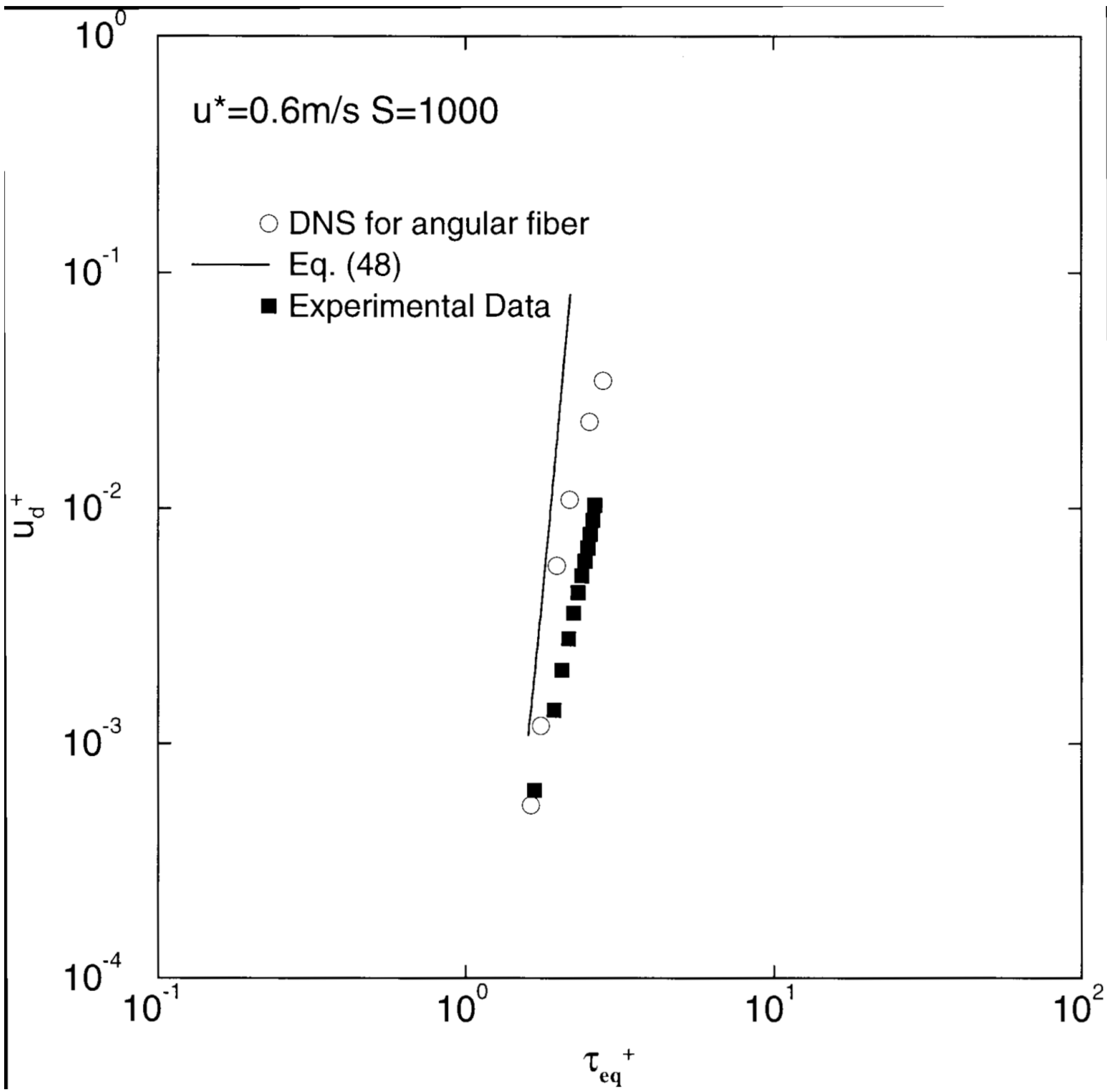

Angular Fiber Deposition Velocity

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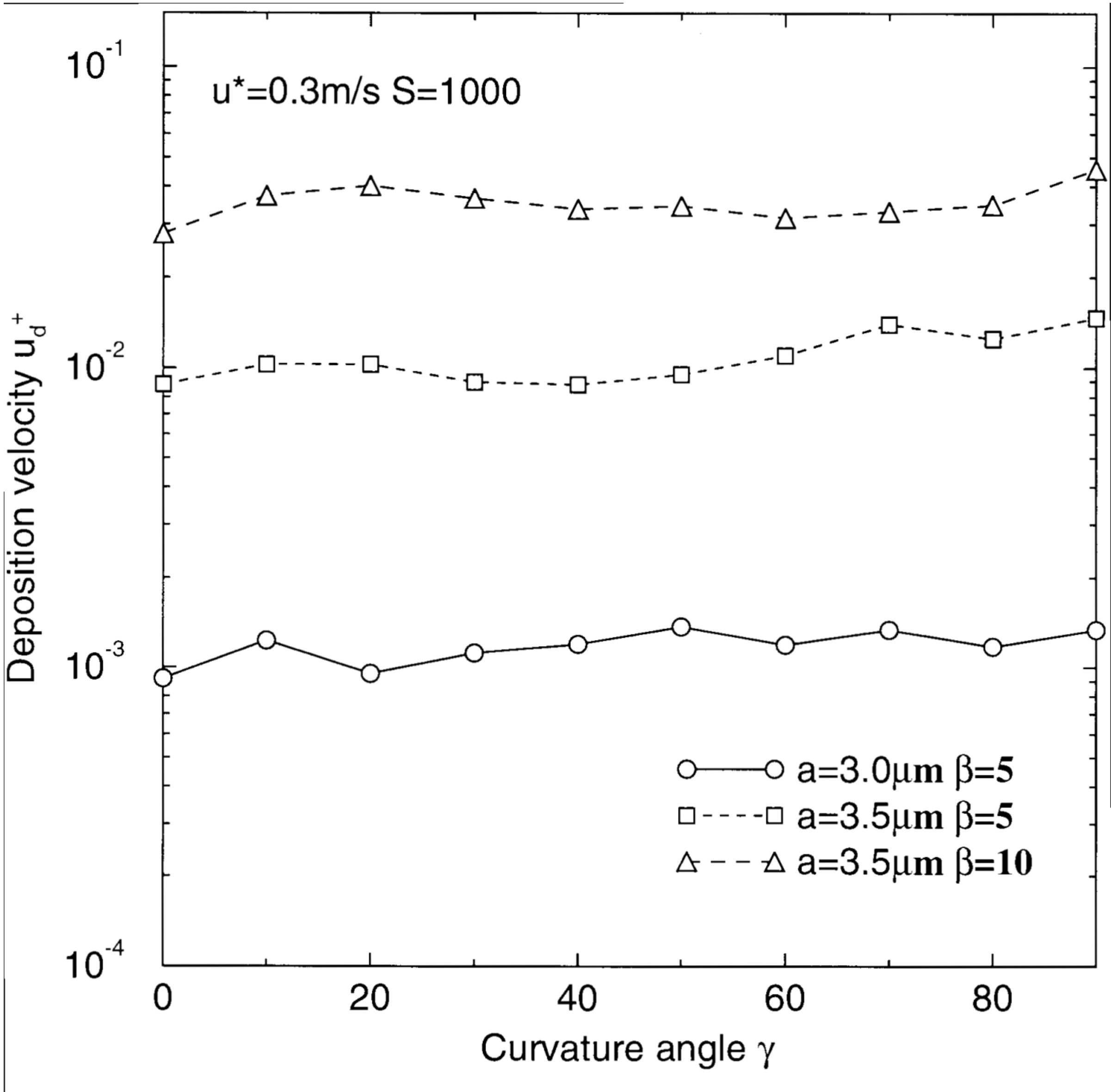

Comparison of Deposition Velocities

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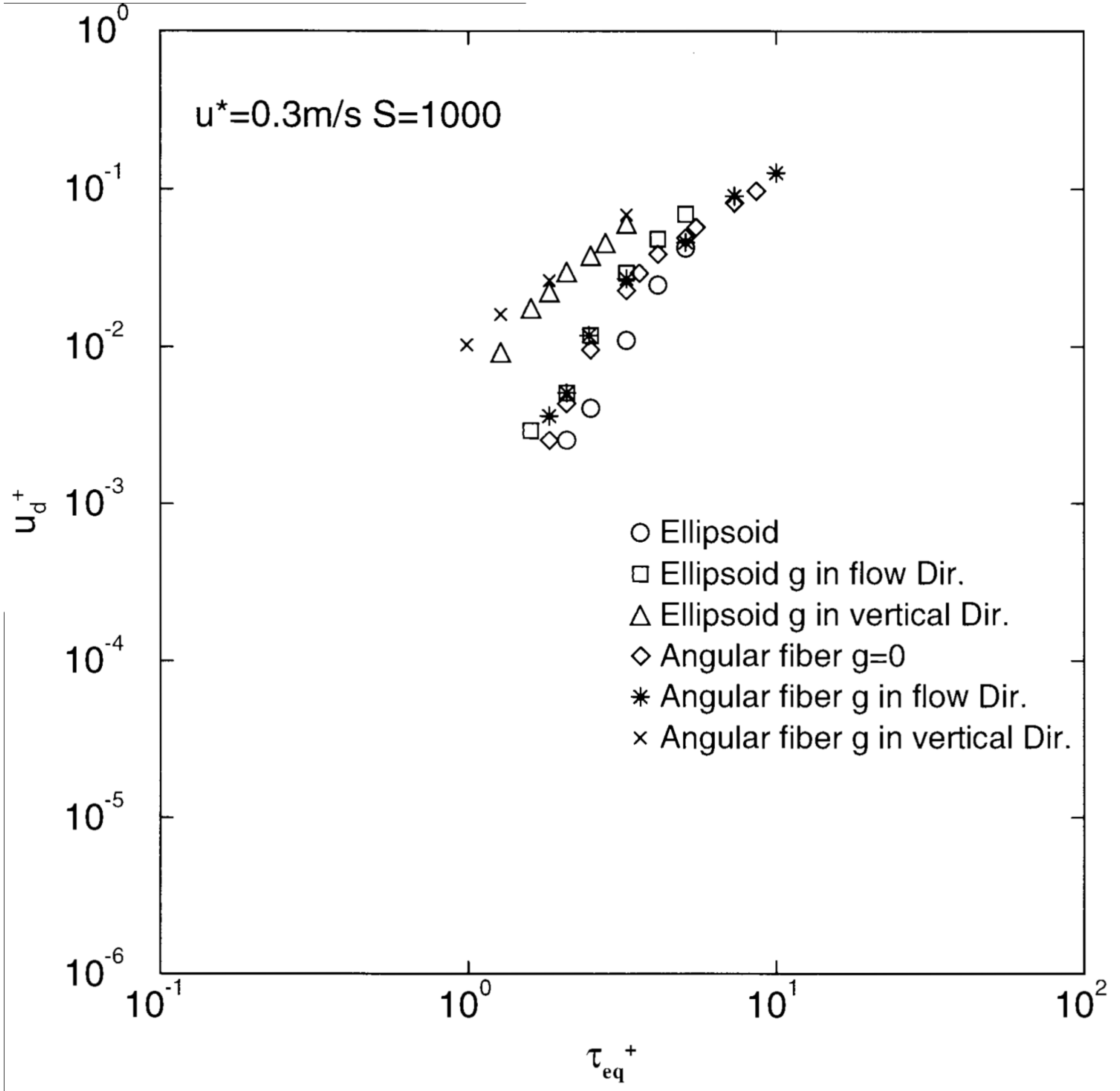

Comparison of Deposition Velocities

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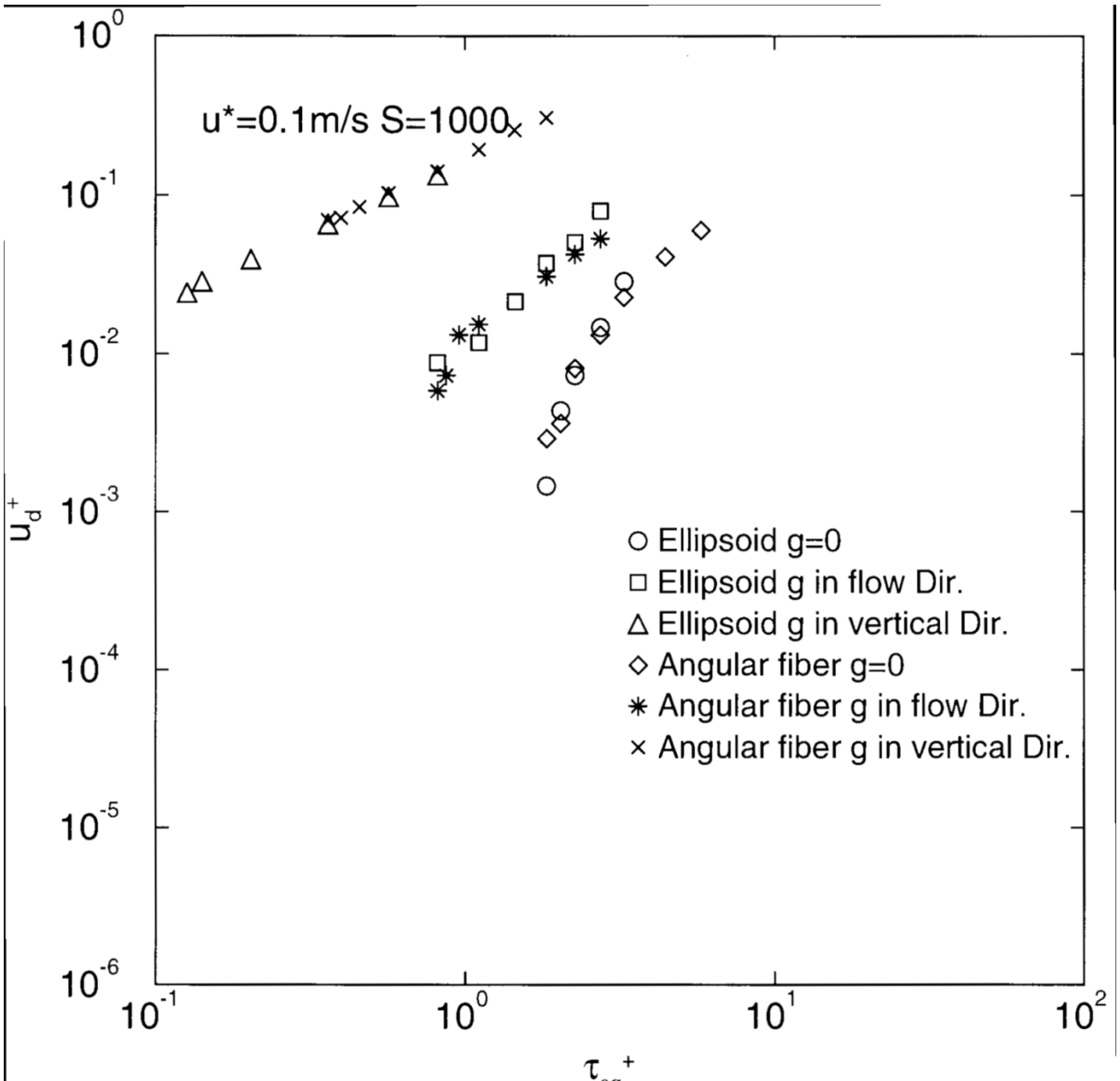

Curly Fiber Motions

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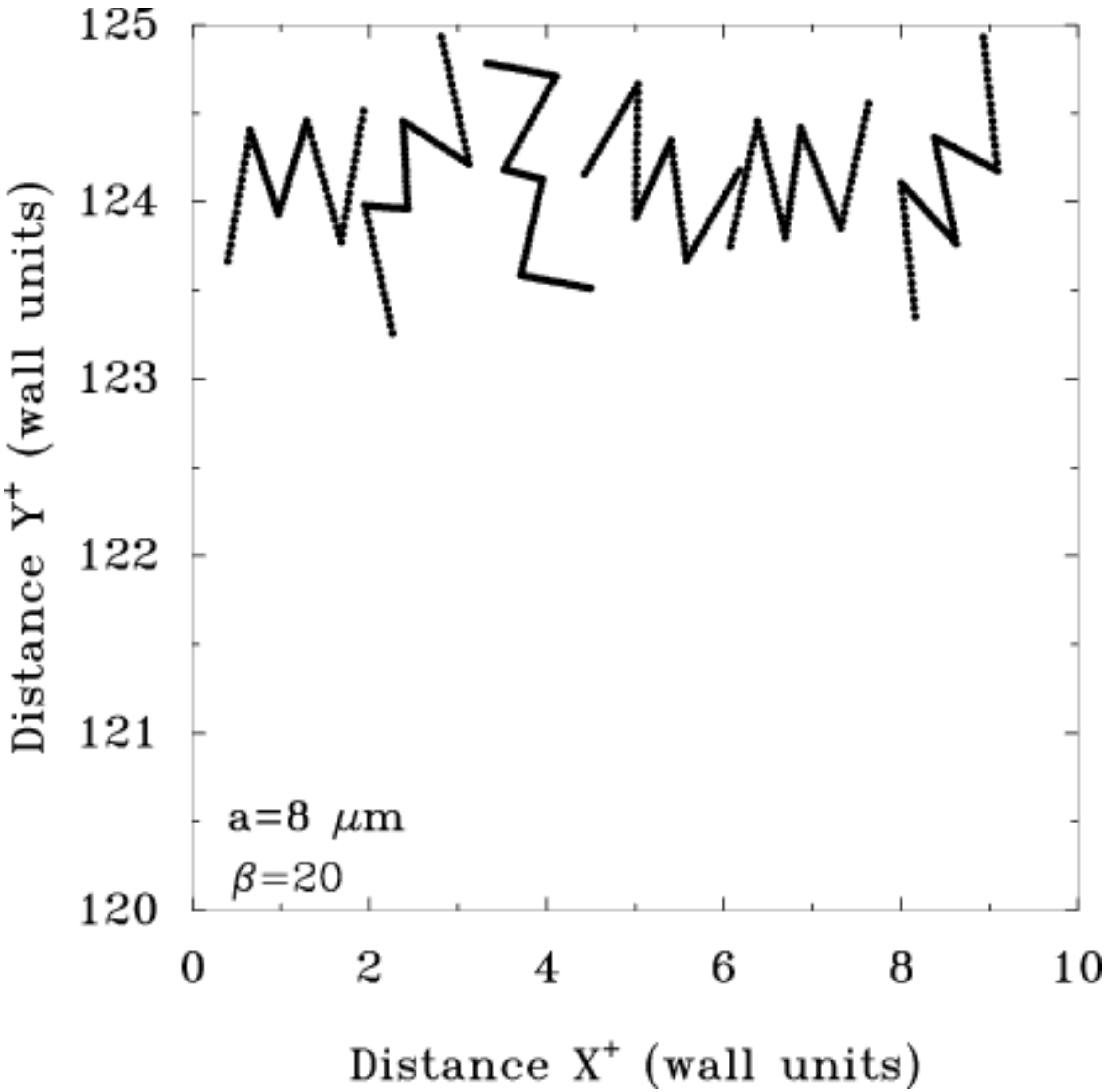

Concluding Remarks

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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.**

Conclusions

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- Aspect ratio plays an important role on ellipsoidal particle deposition rate.
- The simulation results for deposition velocity are in good agreement with the experimental data.
- Deposition velocity increases with fiber aspect ratio.
- Effect of gravity on particle deposition velocity depends on the magnitude of shear velocity.
- The gravitational sedimentation enhances the deposition rate on the lower wall in horizontal duct flows.

Thank You!

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Questions?