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Particle and Fiber Transport and Deposition in Ducts – RANS and Sublayer Models

Goodarz Ahmadi
ahmadi@clarkson.edu
Coulter School of Engineering
Clarkson University, Potsdam, NY 13699-5700

Outline

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- Introduction to Aerosol Transport and Deposition
- RANS Computational Models
- Sublayer Models
- Spherical and Fiber Transport and Deposition
- Conclusions

Definition

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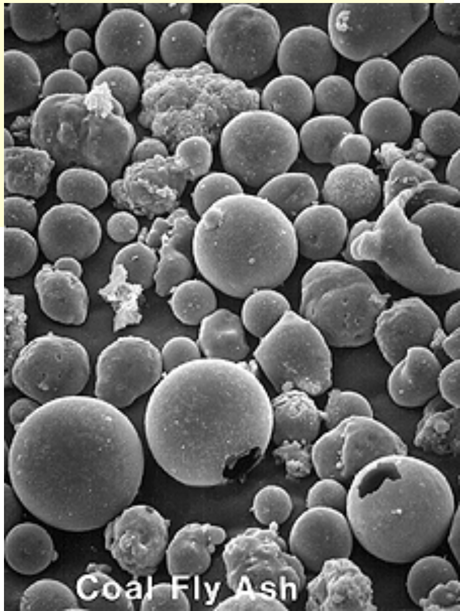
- Aerosols are suspension of solid or liquid particles in a gas.
- Dust, smoke, mists, fog, haze, and smog are common aerosols.
- Aerosol particles are found in different shapes.



Aerosols in the Atmosphere

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	Aerosols	Air
Number Density (Number/cm)	$100\text{-}10^5$	10^{19}
Mean Temperature (K)	240 – 310	240 – 310
Mean Free Path	Greater than 1 m	0.06 μm
Particle Radius	0.01 – 10 μm	2×10^{-4} μm
Particle Mass (g)	10^{-18} - 10^{-9}	4.6×10^{-23}
Particle Charge (Elementary Charge Units)	0 – 100	Weakly Ionized Single Charge

Dimensionless Groups

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Knudsen Number	$Kn = \frac{2\lambda}{d}$
Mach Number	$M = \frac{\lvert \mathbf{v}^p - \mathbf{v}^f \rvert}{c^f}$
Schmidt Number	$Sc = \frac{\nu}{D} = \frac{n^f \lambda d^2}{4}$
Brown Number	$Br = \left(\frac{\overline{v^{p,2}}}{\overline{v^{f,2}}}\right)^{1/2} = \frac{\lvert \overline{v'^p} \rvert}{\lvert \overline{v'^f} \rvert}$
Reynolds Number	$Re = \frac{\lvert \mathbf{v}^p - \mathbf{v}^f \rvert d}{\nu} = \frac{4M}{K_n}$

Mean Free Path

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$$\lambda = \frac{1}{\sqrt{2}\pi n d_m^2} = \frac{kT}{\sqrt{2}\pi d_m^2 P}$$

Molecular Diameter

$$k = 1.38 \times 10^{-23}\ \mathrm{J/K}$$

Air

$$\lambda(\mu m) = \frac{23.1T}{P}$$

Aerosols Characteristics

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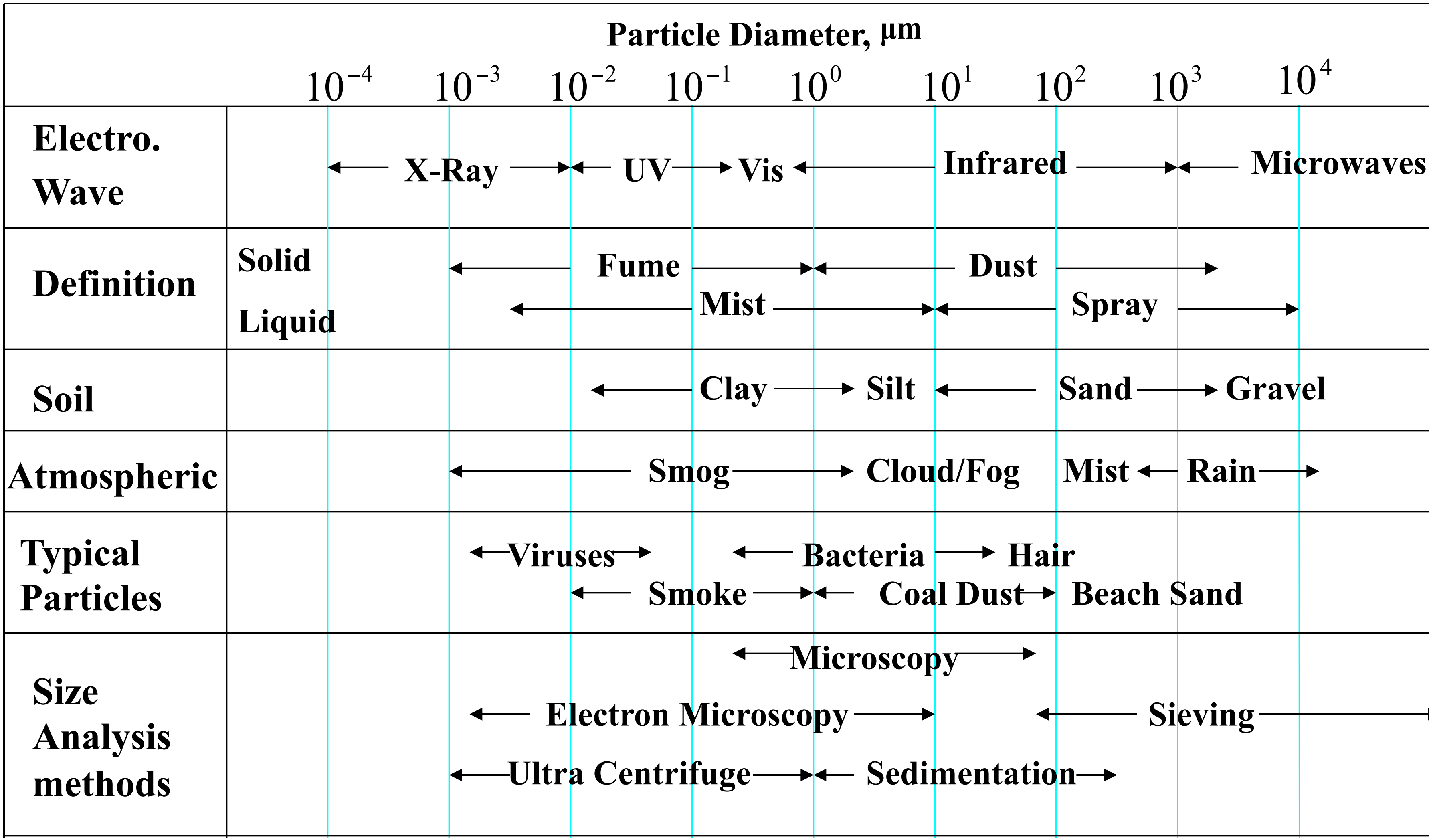

Aerosols Characteristics

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		Particle Diameter, μm								
		10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}	10^{3}	10^{4}
Gas Cleaning Method		**Ultrasonic**; **Settling Chamber**; **Centrifuge**; **Air Filter**; **HE Air Filter**; **Impact Separator**; **Thermal Separator**; **Electrostatic Separator**								
Diffusion Coeff. cm²/s	**Air**		5×10^{-2}		10^{-5}		2×10^{-9}		2×10^{-11}	
	Water		5×10^{-6}		5×10^{-8}		5×10^{-10}		5×10^{-12}	
Terminal Velocity cm/s S=2	**Air**		10^{-6}		2×10^{-4}		0.6		600	
	Water		10^{-10}		6×10^{-7}		6×10^{-3}		12	

Hydrodynamic Forces

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Drag Forces

Stokes ⇒

$$F = 3\pi\mu U d$$

Drag Coefficient ⇒

$$C_D = \frac{F_D}{\frac{1}{2}\rho U^2 A} = \frac{24}{Re}$$

Reynolds Number ⇒

$$Re = \frac{\rho U d}{\mu}$$

Drag Force for a Sphere

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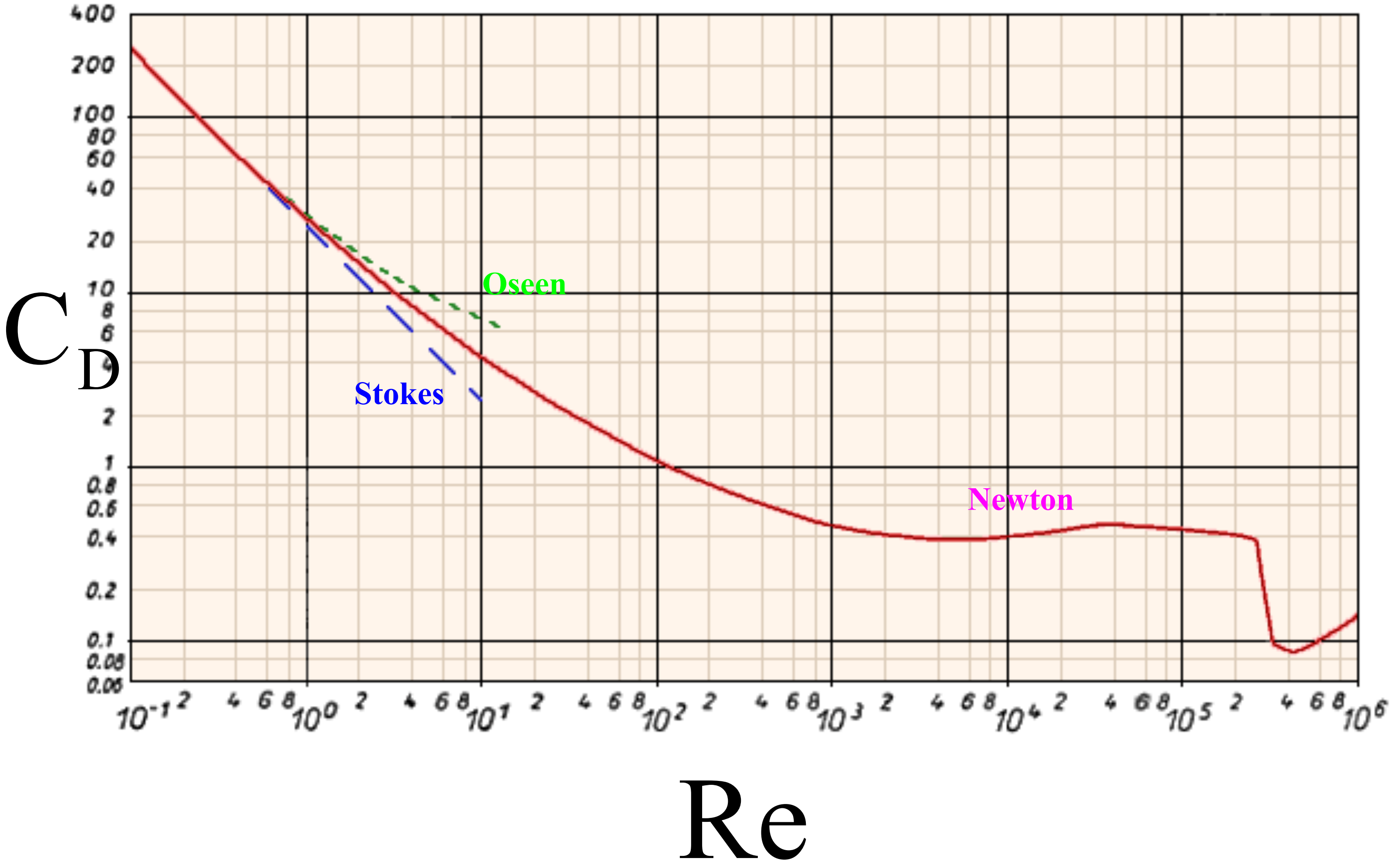

Hydrodynamic Forces

Drag Forces

Oseen

$$C_D = \frac{24[1 + 3\,Re/16]}{Re}$$

$$1 < Re < 1000$$

$$C_D = \frac{24[1 + 0.15\,Re^{0.687}]}{Re}$$

Newton

$$10^3 < Re < 2.5 \times 10^5$$

$$C_D = 0.4$$

Cunningham Correction

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For 1000 > Kn > 0

Stokes-Cunningham Drag

$$F_D = \frac{3\pi\mu U d}{C_c}$$

Cunningham Correction

$$C_c = 1 + \frac{2\lambda}{d}\left[1.257 + 0.4 e^{-1.1d/2\lambda}\right]$$

Cunningham Correction

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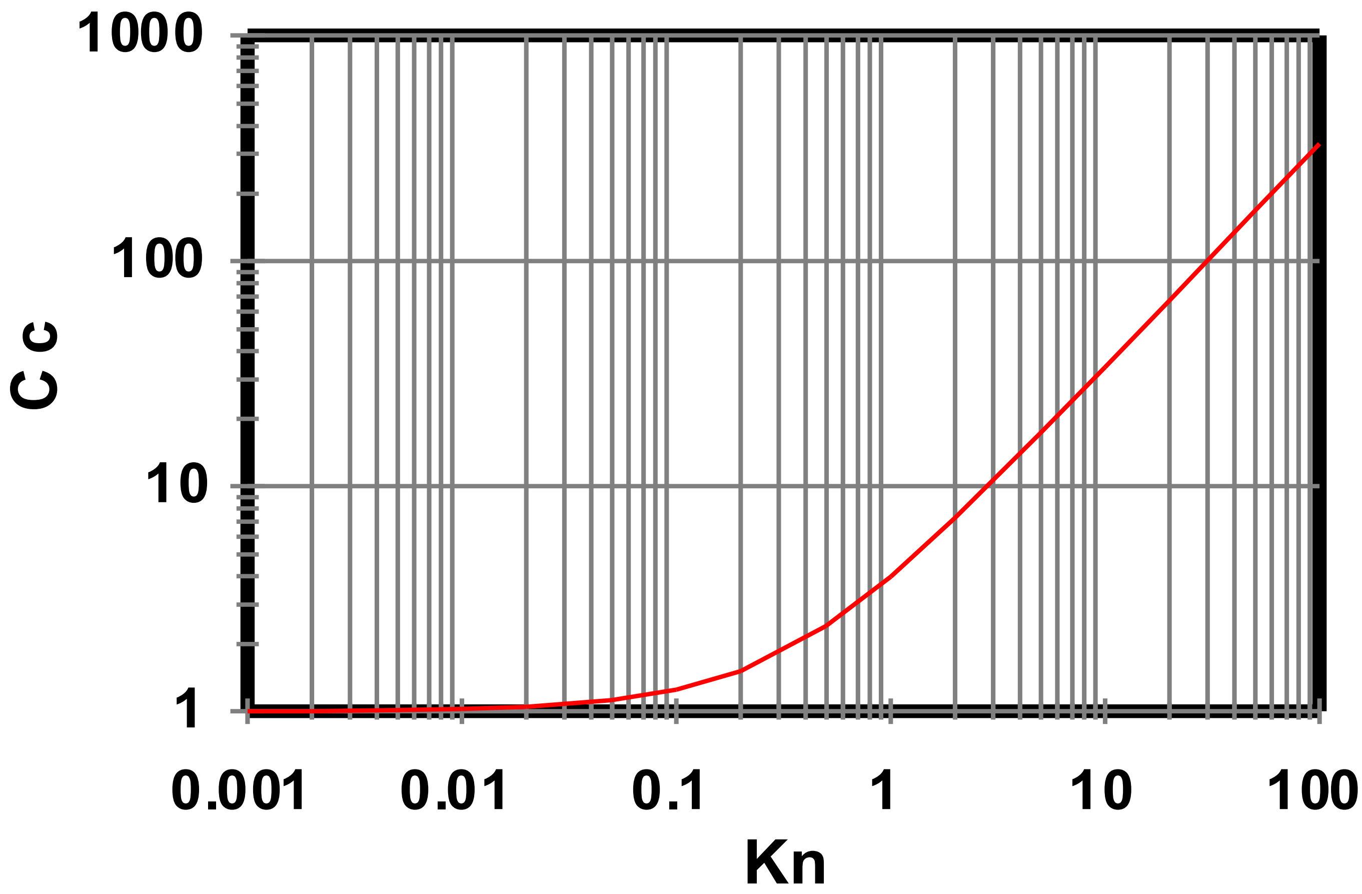

Variation of Cunningham correction with Knudsen number.

Non-Spherical Particles

$$F_D = 3\pi\mu U d_e K$$

$$d_e = \left(\frac{6}{\pi}\text{Volume}\right)^{1/3}$$

K=Correction Factor

Correction Factor

Cluster Shape	Correction	Cluster Shape	Correction	Cluster Shape	Correction
00	K = 1.12	0000	K = 1.32	00 00	K = 1.17
000	K = 1.27	00000	K = 1.45	0 0 0 0 0	K = 1.19
0 0 0	K = 1.16	000000	K = 1.57	00 00 00	K = 1.17
000000 0 0	K = 1.64	0000000	K = 1.73		

Ellipsoidal Particles

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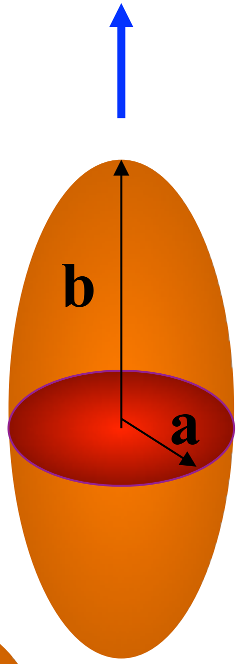
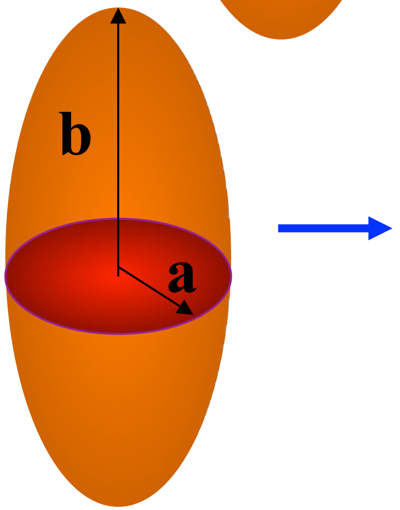
$$F_D = 6\pi\mu U a K'$$

$$\beta = \frac{b}{a}$$

$$K' = \frac{\frac{4}{3}(\beta^2 - 1)}{\frac{(2\beta^2 - 1)}{(\beta^2 - 1)^{1/2}}\ln[\beta + (\beta^2 - 1)^{1/2}] - \beta}$$

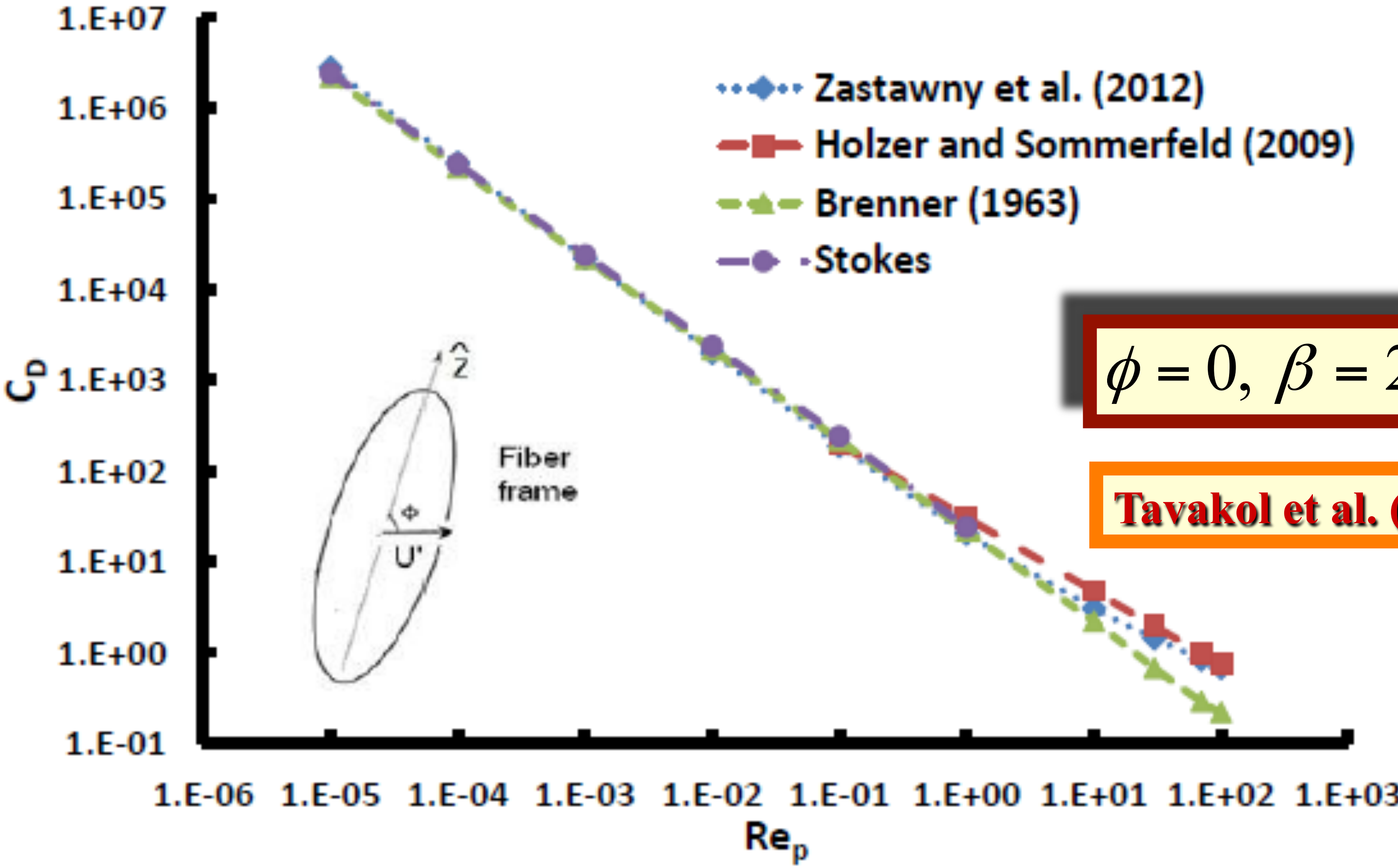


$$K' = \frac{\frac{8}{3}(\beta^2 - 1)}{\frac{(2\beta^2 - 3)}{(\beta^2 - 1)^{1/2}}\ln[\beta + (\beta^2 - 1)^{1/2}] + \beta}$$



Ellipsoidal Particles

Comparison of creeping and non-creeping drag



$\phi = 0, \ \beta = 2$

Tavakol et al. (2015)

Ellipsoidal Particles

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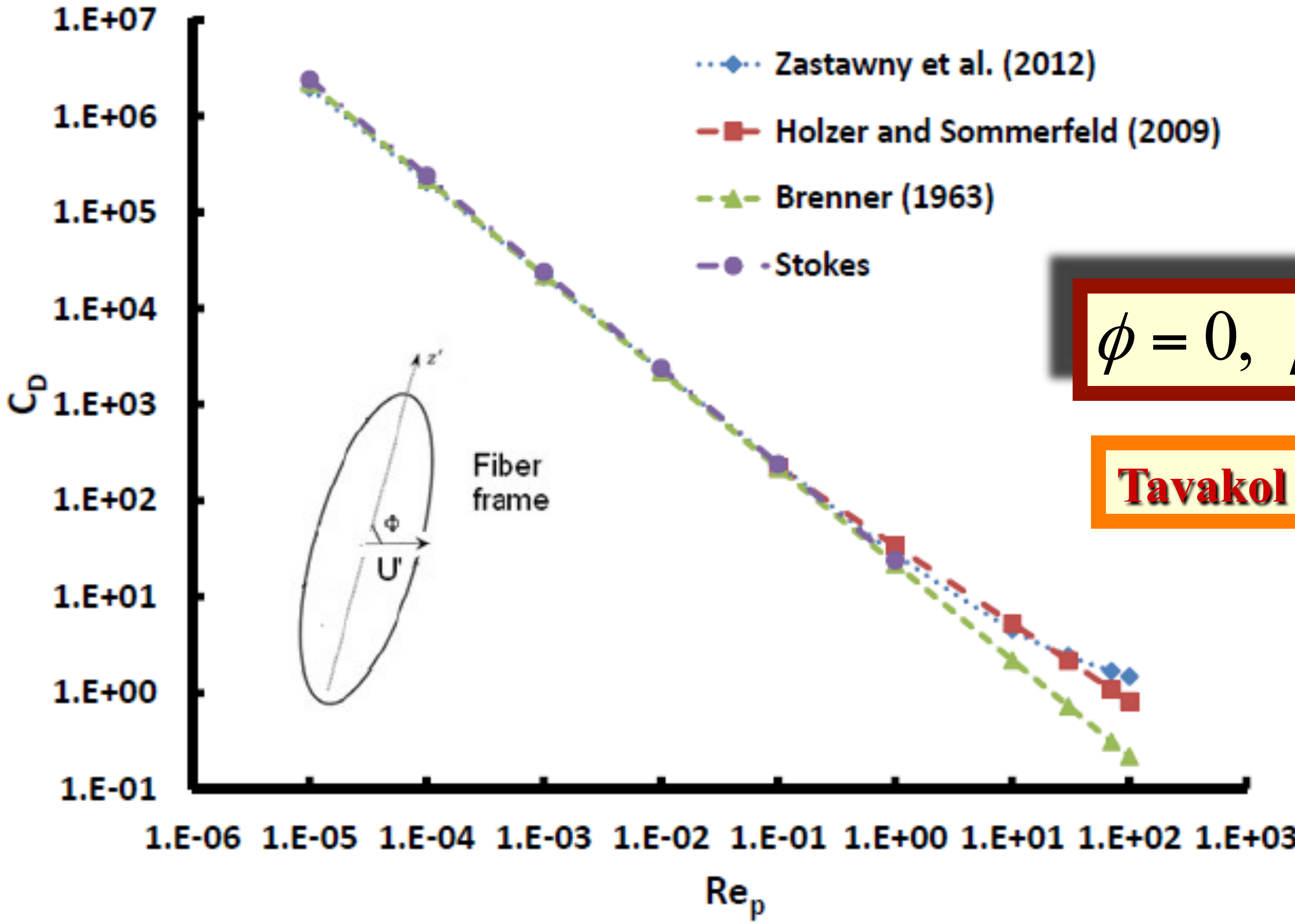
Comparison of creeping and non-creeping drag



$$\phi = 0, \quad \beta = 2$$

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Ellipsoidal Particles

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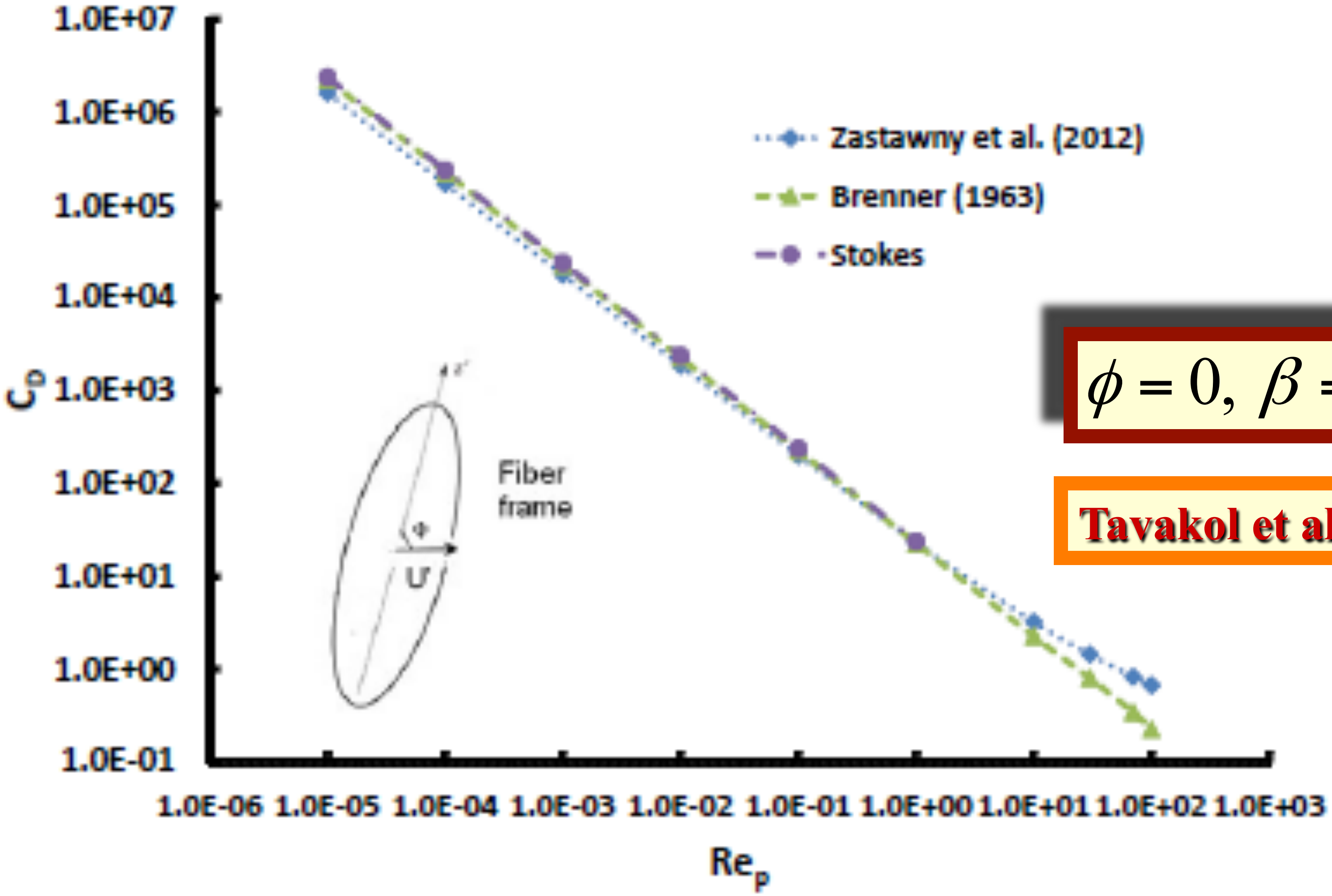
Comparison of creeping and non-creeping drag



$\phi = 0, \ \beta = 5$

Tavakol et al. (2015)

Ellipsoidal Particles

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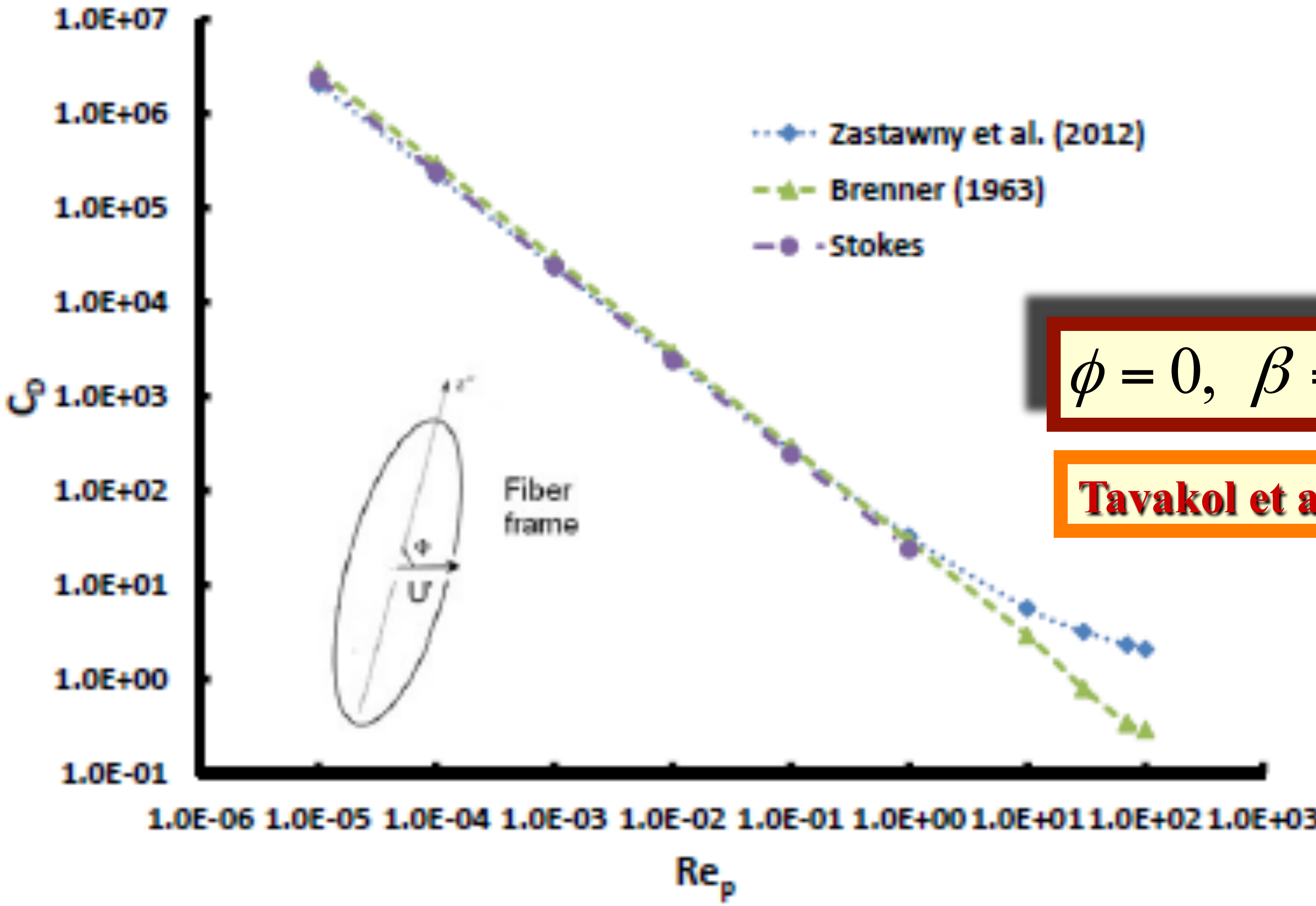
Comparison of creeping and non-creeping drag



$$\phi = 0, \ \ \beta = 5$$

Tavakol et al. (2015)

Ellipsoidal Particles

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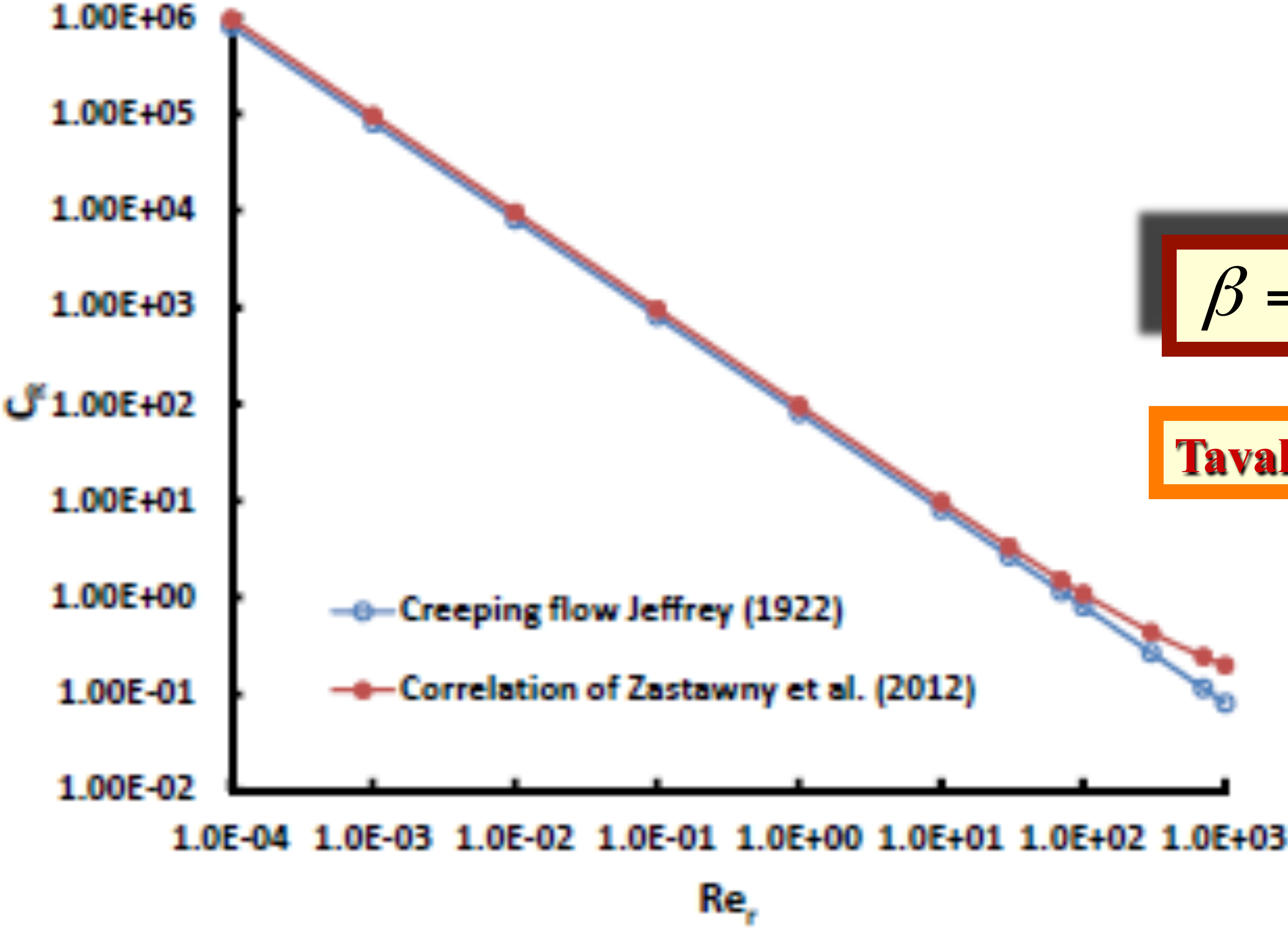
Comparison of creeping and non-creeping torque



$\beta = 2$

Tavakol et al. (2015)

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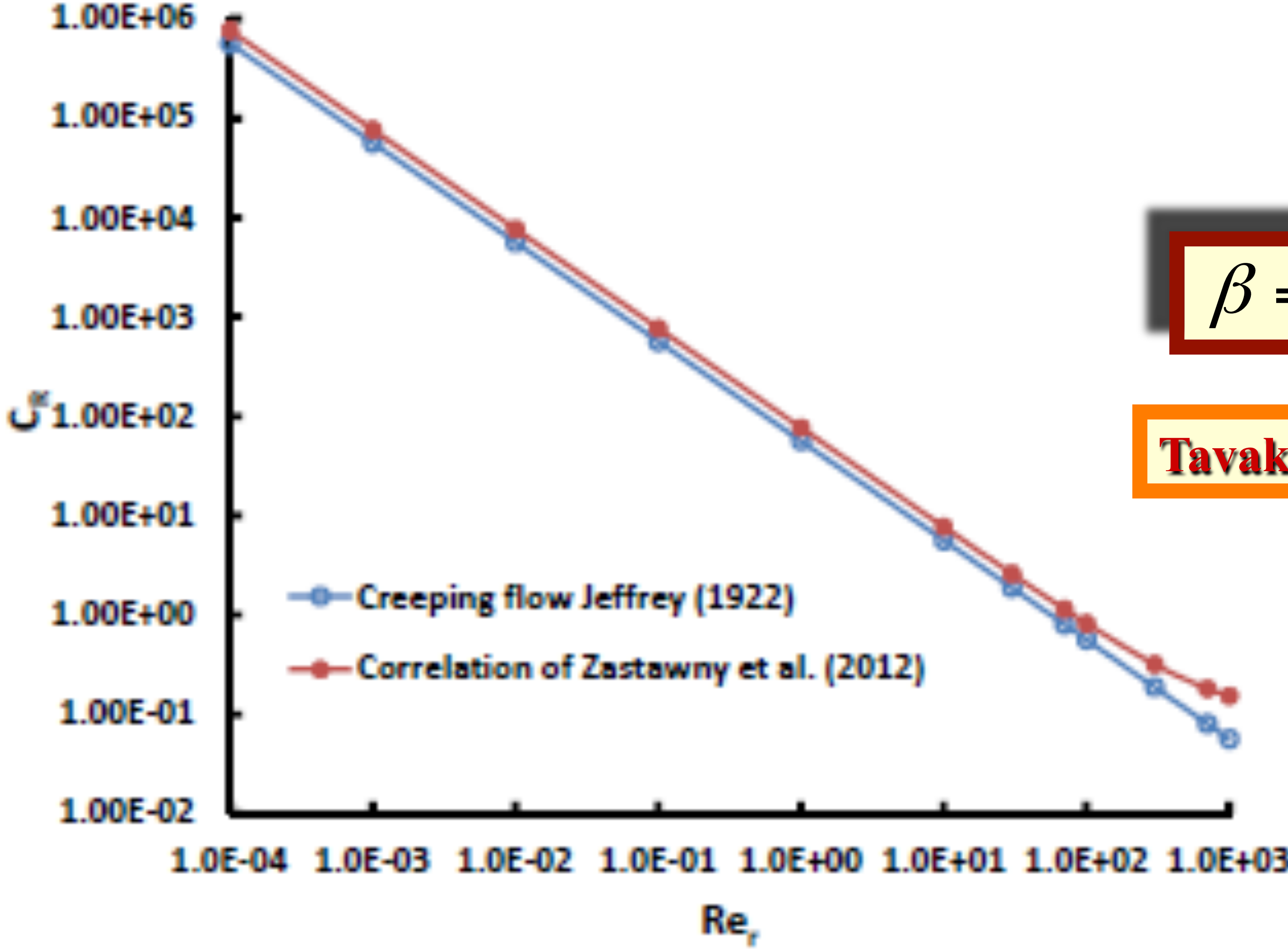
Comparison of creeping and non-creeping torque



$\beta = 5$

Tavakol et al. (2015)

Ellipsoidal Particles

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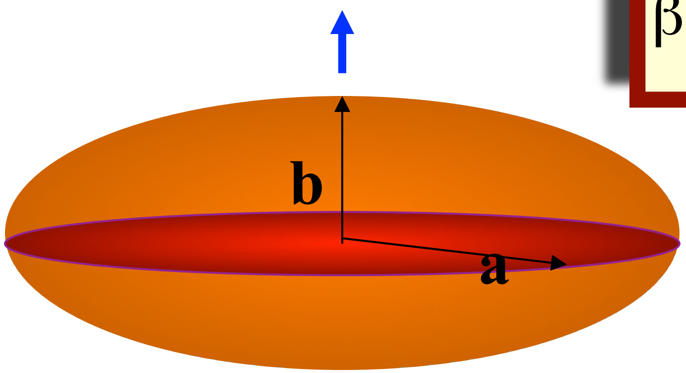
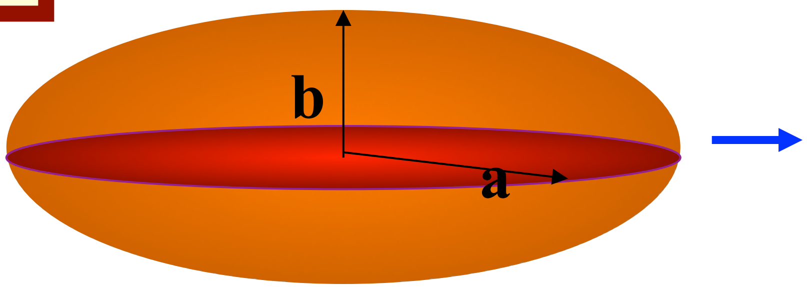
$$\beta = \frac{a}{b}$$





$$K' = \frac{\frac{4}{3}(\beta^2 - 1)}{\frac{\beta(\beta^2 - 2)}{(\beta^2 - 1)^{1/2}} \tan^{-1}(\beta^2 - 1)^{1/2}] + \beta}$$

$$K' = \frac{\frac{8}{3}(\beta^2 - 1)}{\frac{\beta(3\beta^2 - 2)}{(\beta^2 - 1)^{1/2}} \tan^{-1}(\beta^2 - 1)^{1/2}] - \beta}$$

Thin Disks

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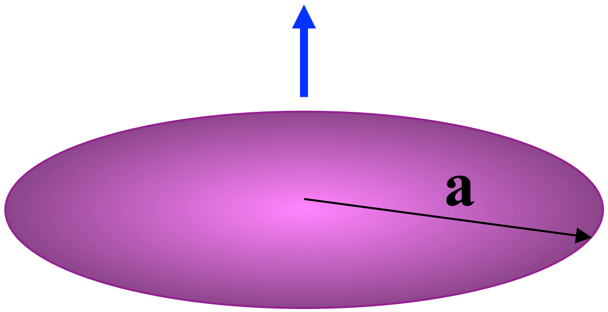
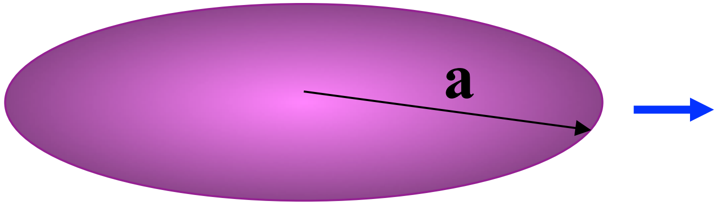
$$F_D = 16\mu a U$$



$$F_D = 32\mu a U/3$$



Thin Disks

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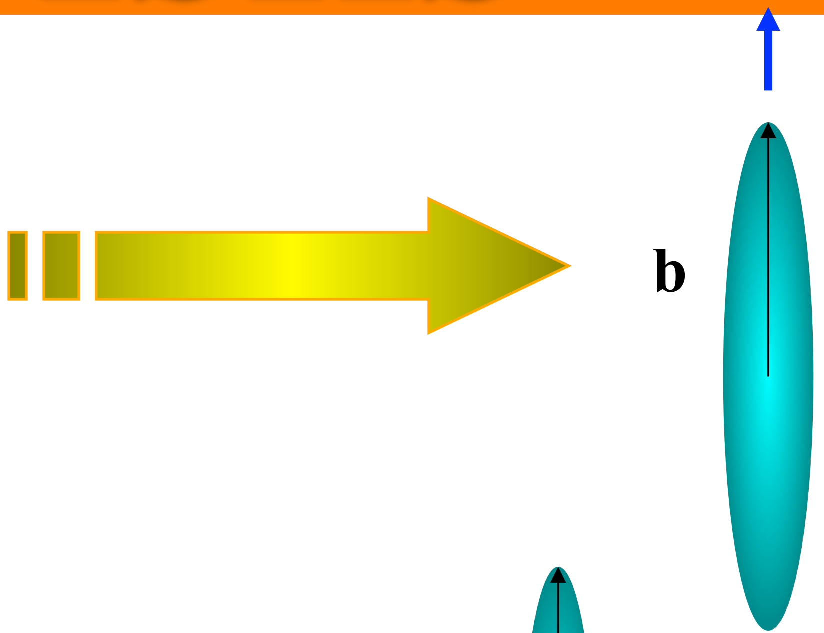
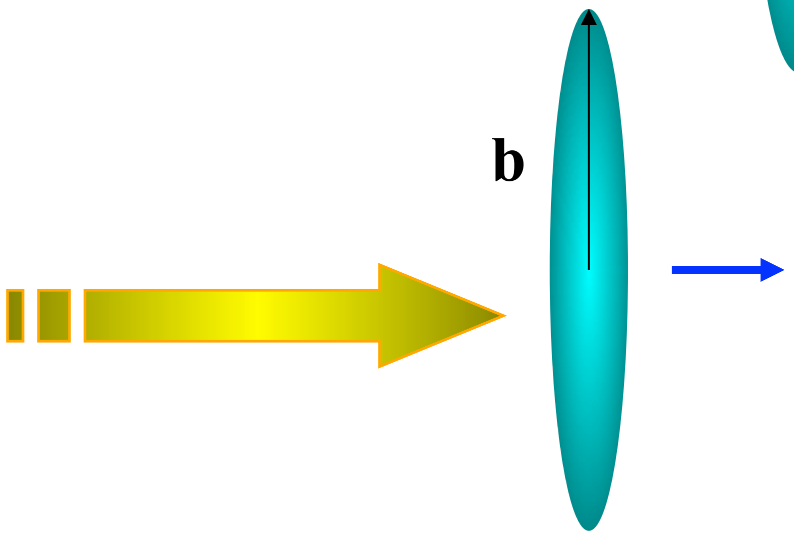
$$F_D = \frac{4\pi\mu U b}{\ln 2\beta}$$



$$F_D = \frac{8\pi\mu U b}{\ln 2\beta}$$



Cylindrical Needle

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$$F_D = \frac{4\pi\mu U}{(2.002 - \ln R_e)}$$

$$R_e = \frac{2aU}{\nu}$$

Aerosols Particle Motion

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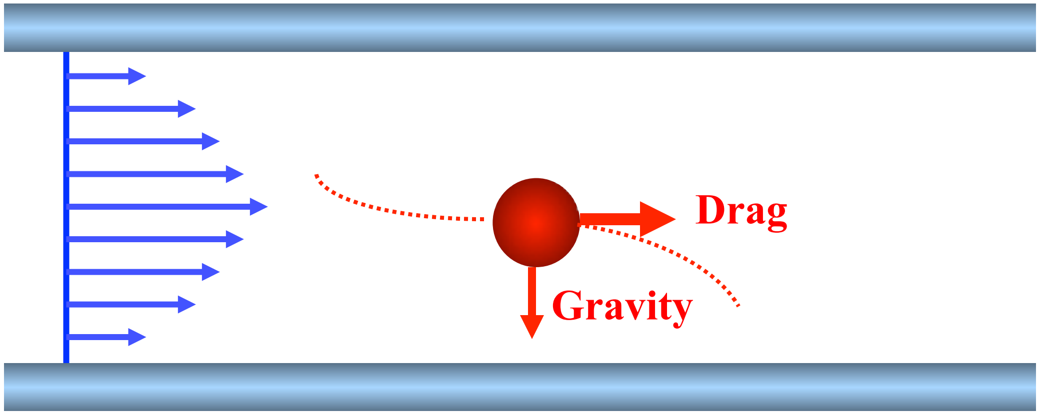

Equation of Motion

$$m\frac{d\mathbf{u}^p}{dt} = \frac{3\pi\mu d}{C_c}(\mathbf{u}^f - \mathbf{u}^p) + m\mathbf{g}$$

Aerosols Particle Motion

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$$\tau \frac{d\mathbf{u}^p}{dt} = (\mathbf{u}^f - \mathbf{u}^p) + \tau \mathbf{g}$$

Relaxation Time

$$\tau = \frac{mC_c}{3\pi\mu d} = \frac{d^2 \rho^p C_c}{18\mu} = \frac{S d^2 C_c}{18\nu}$$

$$S = \frac{\rho^p}{\rho^f}$$

$$\tau(s) \approx 3 \times 10^{-6} d^2 (\mu m)$$

Terminal Velocity

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$$\mathbf{u}^p = (\mathbf{u}^f + \tau\mathbf{g})(1 - e^{-t/\tau})$$

Terminal Velocity = Equilibrium Velocity after Large Time

$$u^t = \tau g = \frac{\rho^p d^2 g C_c}{18\mu}$$

$$u^t(\mu m/s) \approx 30 d^2(\mu m)$$

Stopping Distance

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Stopping Distance = Penetration distance for an initial velocity of u_o

$$u^p = u_o e^{-t/\tau}$$

$$x^p = u_o^p \tau (1 - e^{-t/\tau})$$

$$x^p = u_o^p \tau$$

$$x^p(\mu m) \approx 3 d^2 (\mu m)$$

Relaxation Time, Terminal Velocity and Stopping Distance

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Diameter, μm	Terminal Velocity	τ sec	Stopping Distance u= 1 m/s	Stopping Distance u= 10 m/s
0.05	0.39 μm/s	4×10^{-8}	0.04 μm	0.0004 mm
0.1	0.93 μm/s	9.1×10^{-8}	0.092 μm	0.0009 mm
0.5	10.1 μm/s	1×10^{-6}	1.03 μm	0.0103 mm
1	35 μm/s	3.6×10^{-6}	3.6 μm	0.0357 mm
5	0.77 mm/s	7.9×10^{-5}	78.6 μm	0.786 mm
10	3.03 mm/s	3.1×10^{-4}	309 μm	3.09 mm
50	7.47 cm/s	7.6×10^{-3}	7.62 mm	76.2 mm

Lift Force

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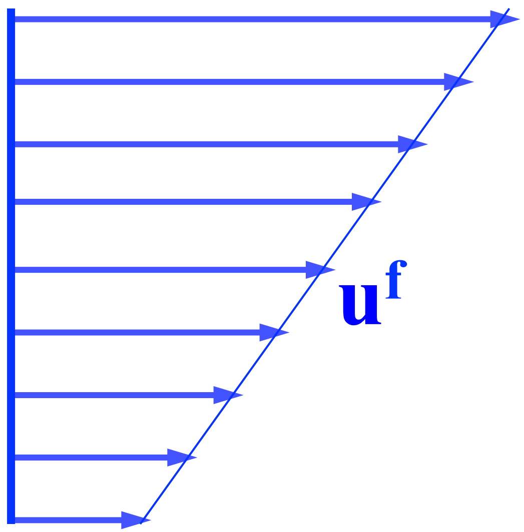

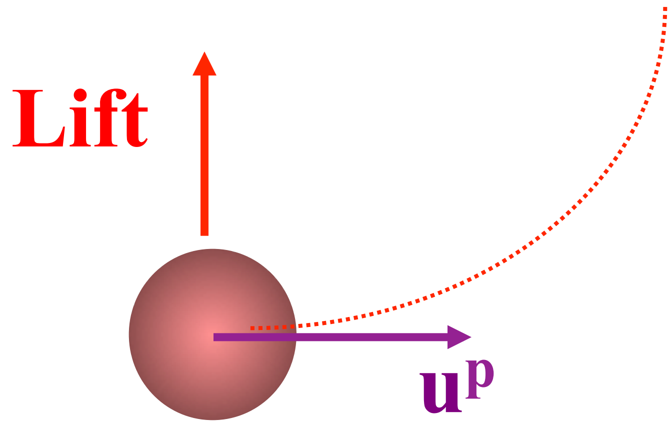

Saffman (1965, 1968)

$$F_{L(Saff)} = 1.615 \rho \nu^{1/2} d^2 (u^f - u^p) \left| \frac{du^f}{dy} \right|^{1/2} \operatorname{sgn}\left(\frac{du^f}{dy} \right)$$

Saffman Lift Force Constraints

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$$R_{es} = \frac{|u^f - u^p|\, d}{\nu} << 1$$

$$R_{eG} = \frac{\dot{\gamma} d^2}{\nu} << 1$$

$$\varepsilon = \frac{R_{eG}^{1/2}}{R_{es}} >> 1$$

Lift Force

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Mai (1992)

McLaughlin (1991)

$$\frac{F_L}{F_{L(Saff)}} = \begin{cases} (1-0.3314\alpha^{1/2})\exp(-R_{es}/10)+0.3314\alpha^{1/2} & \text{for } R_{es} \le 40 \\ 0.0524(\alpha R_{es})^{1/2} & \text{for } R_{es} > 40 \end{cases}$$

$$\alpha = \frac{\dot{\gamma} d}{2|u^f - u^p|} = \frac{R_{es}\varepsilon^2}{2} = \frac{R_{eG}}{2R_{es}}$$

$$\frac{F_L}{F_{L(Saff)}} = 0.3\{1+\tanh[2.5\log_{10}(\varepsilon+0.191)]\}\{0.667+\tan[6(\varepsilon-0.32)]\}$$

$$0.1 \le \varepsilon \le 20$$

Lift Force in Turbulent Boundary Layer

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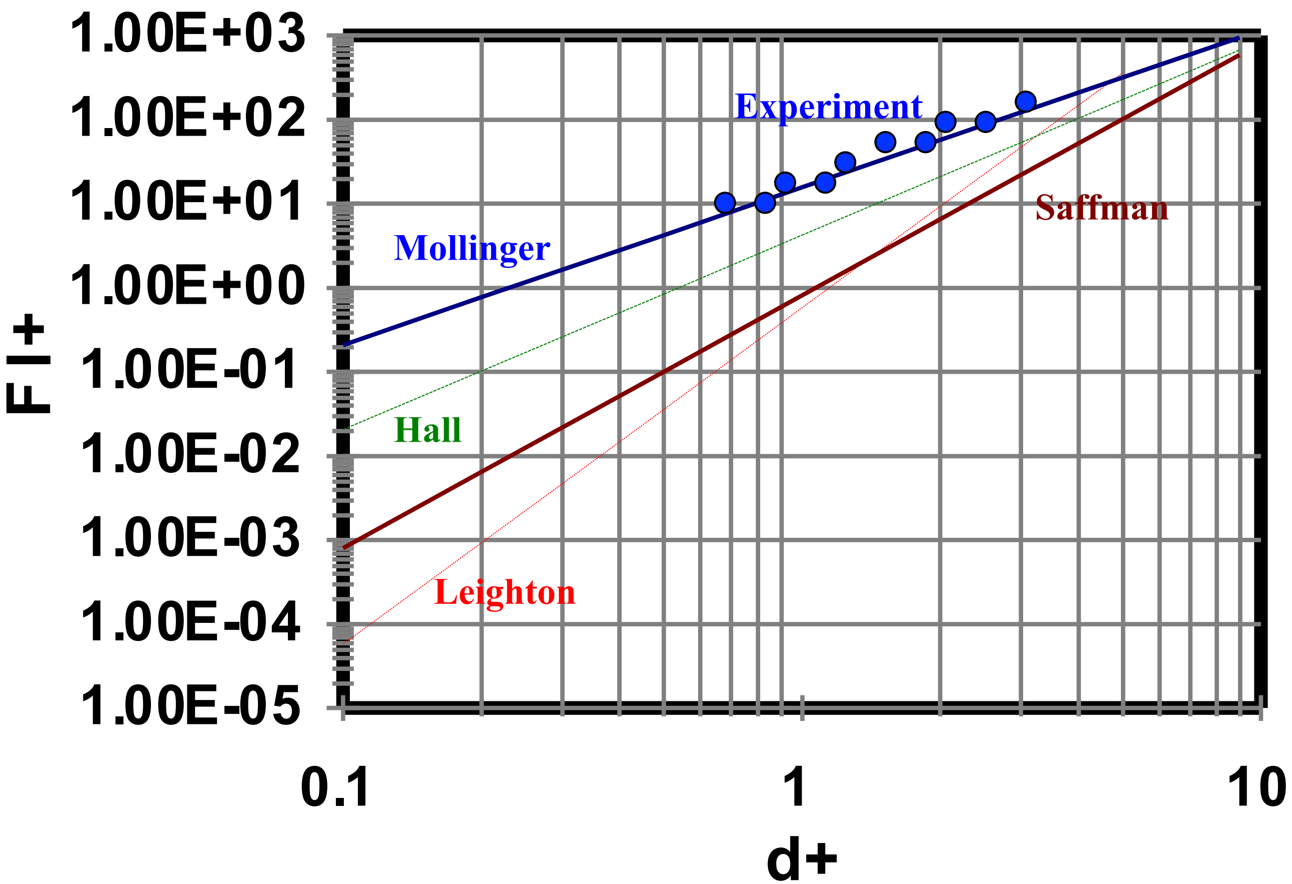

Summary

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- Introduction to Aerosols
- Drag Forces
- Cunningham Corrections
- Lift Forces
- Brownian Motion
- Particle Deposition Mechanisms

Turbulence Deposition Theories

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Mass Flux

$$J = (D + D^T)\frac{\partial C}{\partial y}$$

$$u_D^+ = (D^+ + D^{T+})\frac{\partial C^+}{\partial y^+}$$

Deposition Velocity

$$u_D^+ = \frac{u_D}{u^*} = \frac{1}{u^*}\left(\frac{J}{C_0}\right)$$

$$C^+ = \frac{C}{C_0}$$

$$D^T = \nu^T$$

$$D^{T+} = \nu^{T+}$$

Friedlander and Johnstone Model (Free Flight)

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Eddy Diffusivity

Friedlander and Johnstone (1959)

$$D^{T+} = \nu^{T+} = \begin{cases} \left(\frac{y^+}{14.5}\right)^3 & 0 \le y^+ \le 5 \\ \frac{y^+}{5} - 0.959 & 5 \le y^+ \le 30 \end{cases}$$

$$C(s^+ + \frac{d^+}{2}) = 0$$

Stopping Distance

$$s = U_f \tau$$

Free Flight Velocity

$$U_f = 0.9u^* = 0.9\bar{U}\sqrt{\frac{f}{2}}$$

$$f = C_f = \frac{\tau_0}{0.5\rho \bar{U}^2}$$

Friedlander and Johnstone Model

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Deposition Velocity

$$s^+ = 0.9\tau^+$$

$$u_d^+ = \left(\frac{1}{\sqrt{f/2}} + \frac{1525}{{s^+}^2} - 50.6\right)^{-1} \quad \leftarrow \quad s^+ \le 5$$

$$u_d^+ = \left[\frac{1}{\sqrt{f/2}} - 13.75 + 5\ln\left(\frac{5.04}{0.5s^+ - 0.959}\right)\right]^{-1} \quad \leftarrow \quad 5 \le s^+ \le 30$$

$$u_d^+ = \sqrt{f/2} \quad \leftarrow \quad s^+ \ge 30$$

Turbulence Deposition Theories

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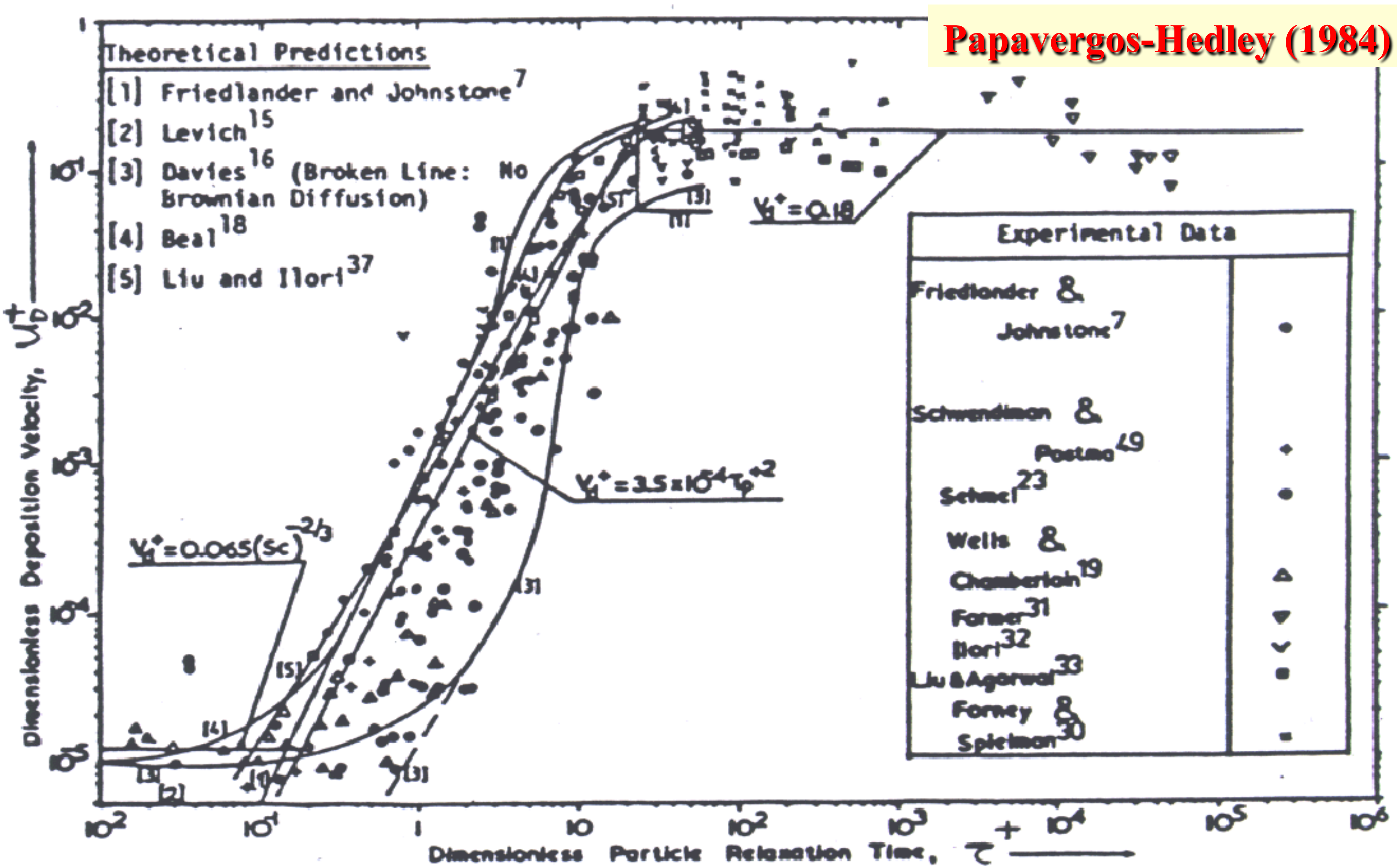

Free Flight Deposition Models

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Levich (1962)

$$\nu^T \sim y^{+4}$$

$$u_D^+ = 0.13337 S_c^{-3/4}$$

Davies

$$u_D^+ = 0.057 s_c^{-2/3}$$

Sehmel

$$D^{T+} = 0.011 (y^+)^{1.1} (\tau^+)^{1.1} \qquad y^+ < 20$$

$$D^{T+} = 0.04 y^+ \qquad y^+ > 20$$

$$U_f^+ = 1.49 (\tau^+)^{-0.49}$$

Liu and Ilory

$$D^{T+} = \nu^{T+} + \left(\frac{y^+}{y^+ + 10}\right)^2 \tau^+$$

Comparisons of Turbulence Deposition Model

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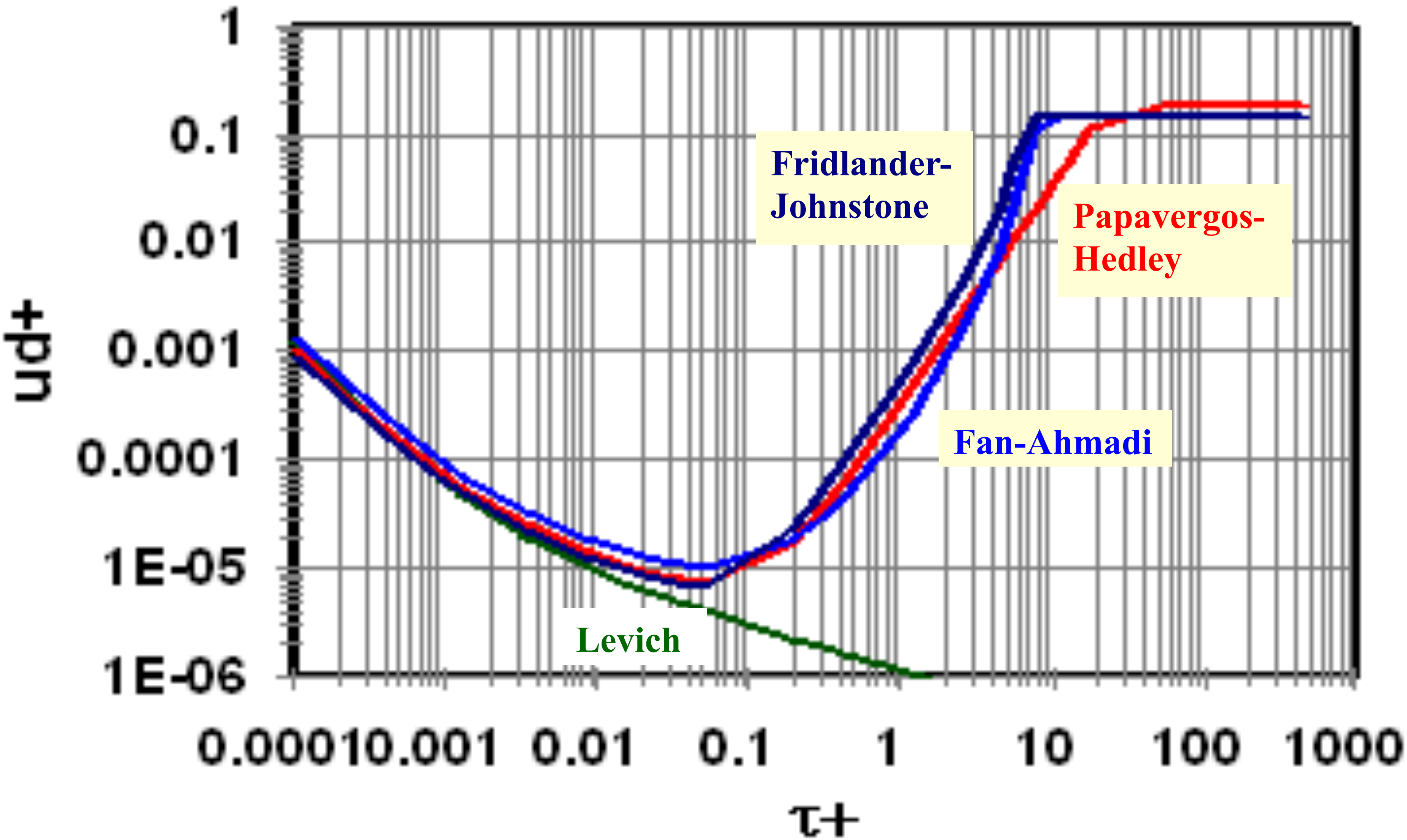

Limitations of Free-Flight Models

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- Use of the concept of 'stopping distance' as a sink boundary condition for particle
- Assumptions for free-flight velocity
- Equality of particle mass diffusivity to the turbulence eddy diffusion.
- Ignoring the effects of density ratio, Reynolds number, and scales of turbulence.
- Ignoring the effects of lift force.
- Ignoring the effects of coherent eddies and bursting phenomena.

Structure of Turbulence Near a Wall

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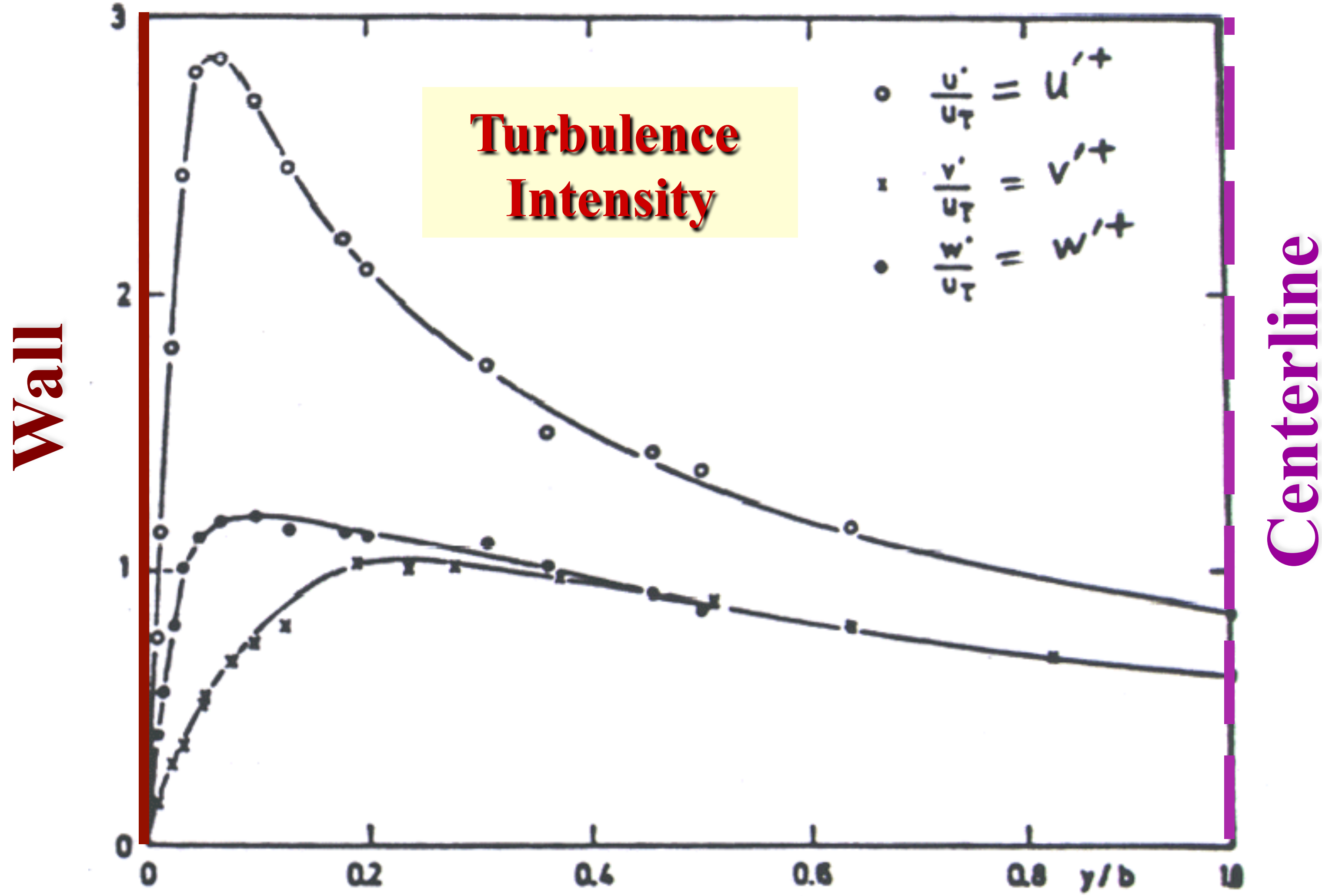

Streaky Wall Flow

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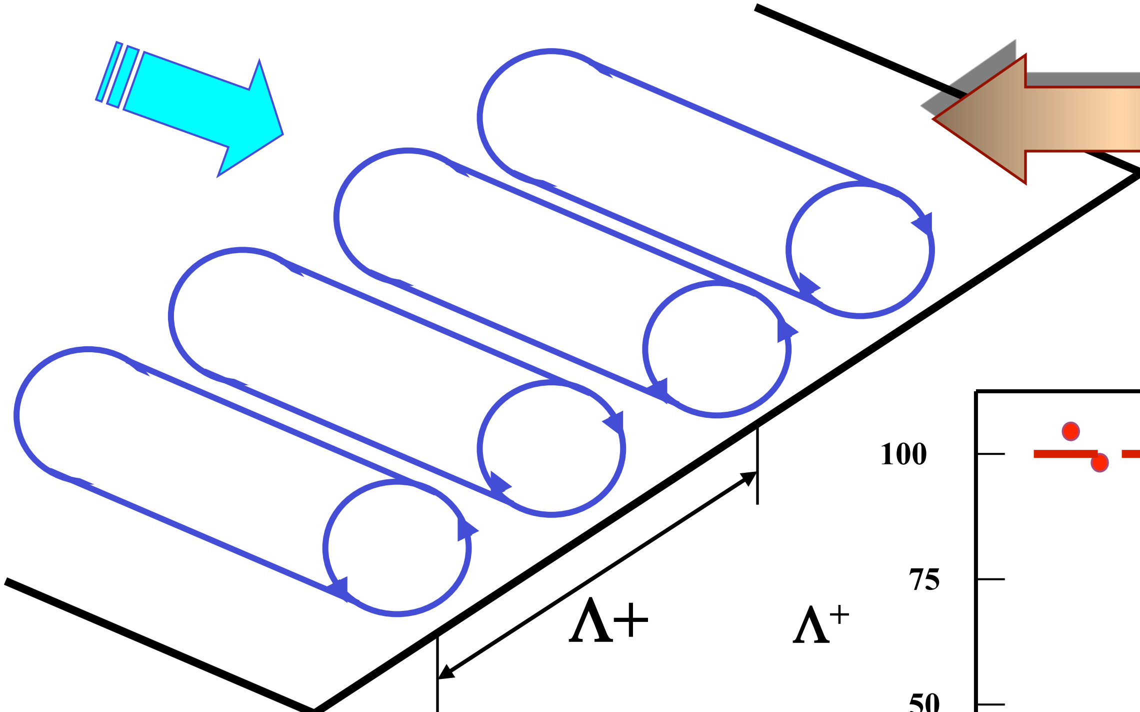
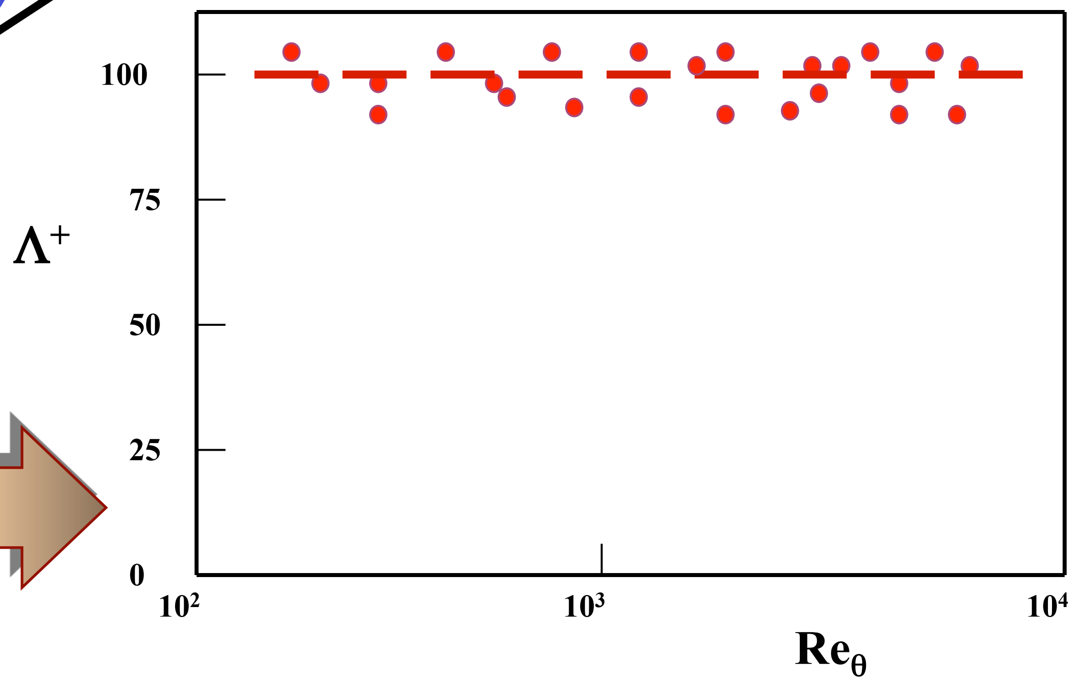
Coherent Eddies



Eddy Spacing



Bursting Phenomena

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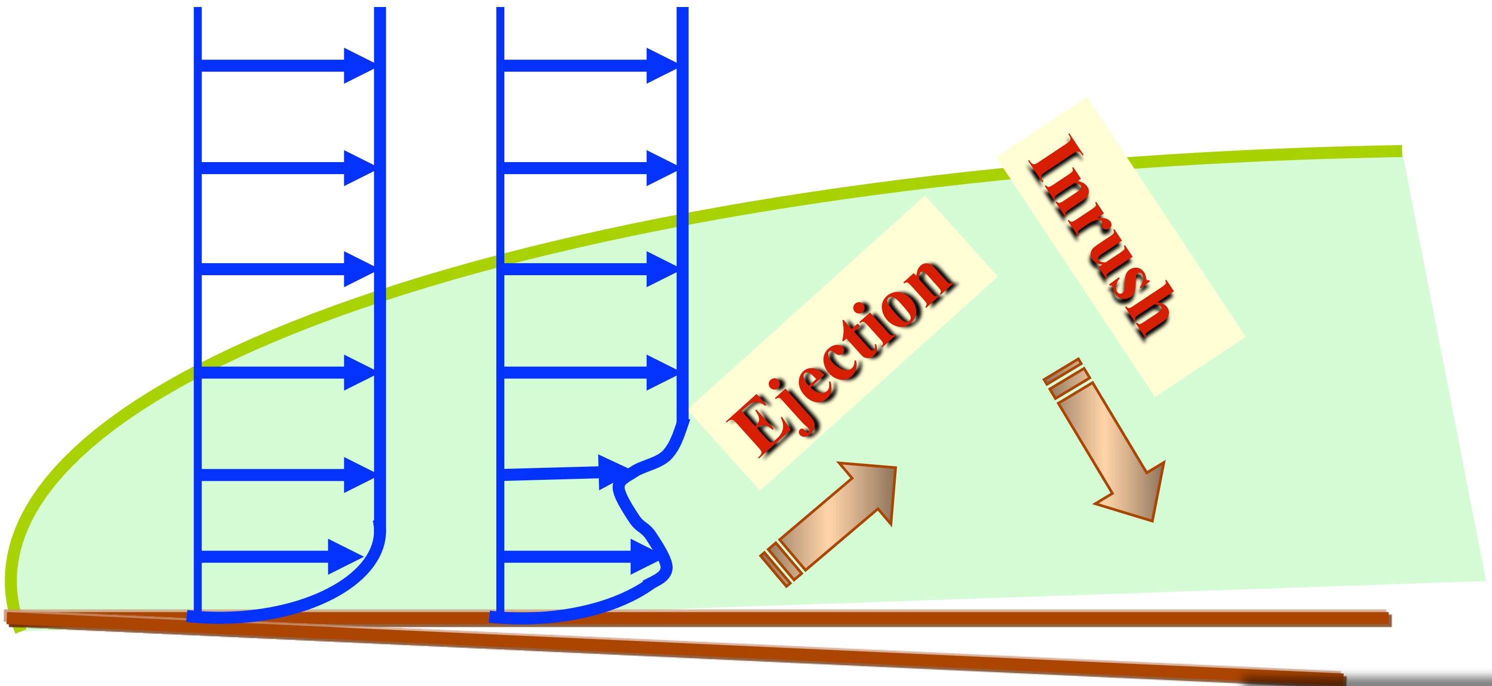

Time Between Bursts

$$T_B^+ = 0.65 R_\theta^{0.73}$$

$$\frac{V_0 T_B}{\delta} \approx 5$$

Bursts Duration

$$0.25 T_B$$

Cleaver and Yates Model

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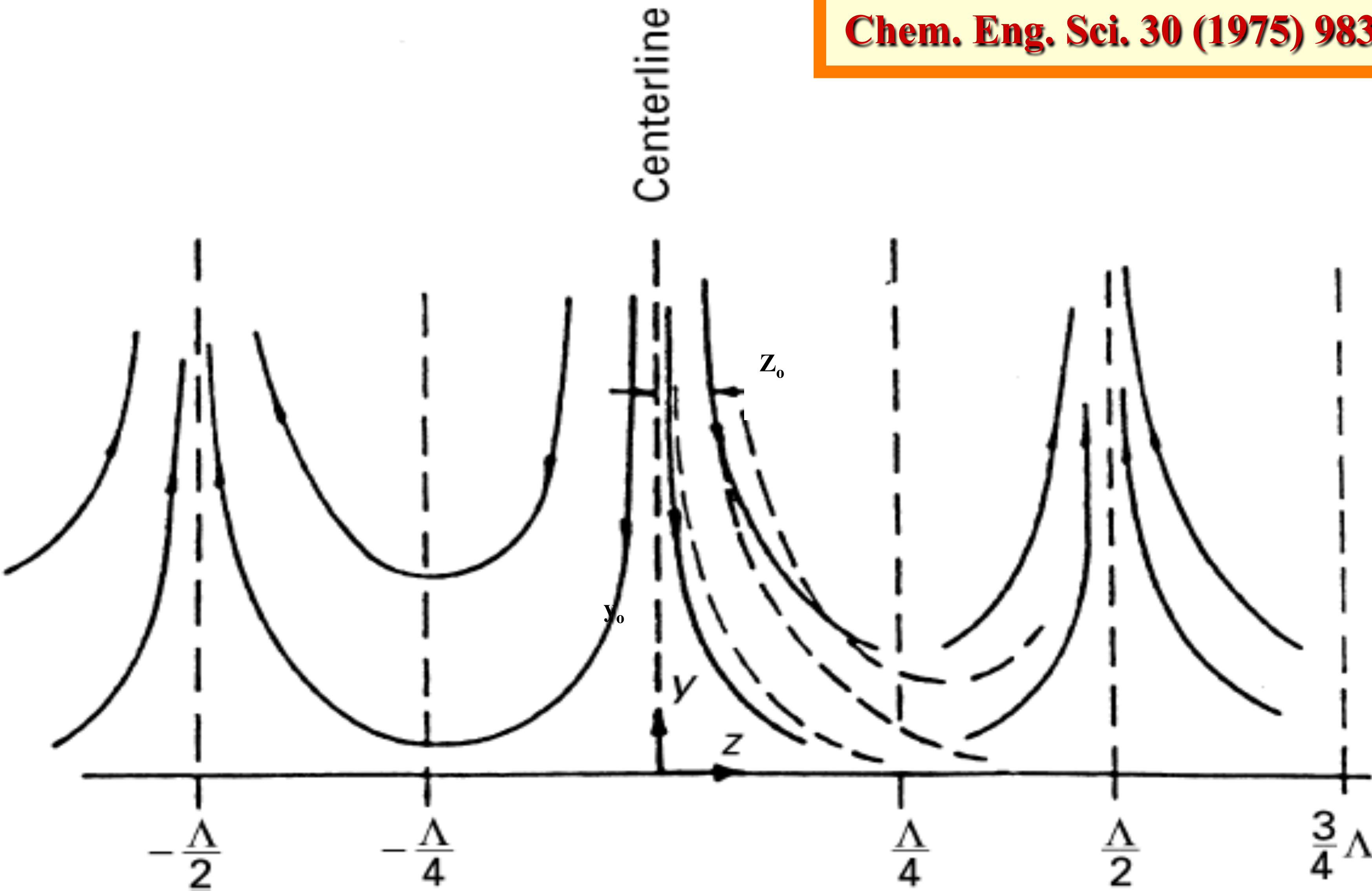
- Suspended particles diffuse to a certain distance from the wall by turbulent diffusion before being entrained in a down-sweep.
- The flow in a down-sweep may be approximated as a two-dimensional stagnation-point flow in the sub-layer.
- Only Stokes drag is acting on the particles.

$$u_D^+ = \frac{9}{400}\frac{\rho^f}{\rho^p}\tau^+ \exp\{0.48\tau^+\} + 0.084 Sc^{-2/3}$$

Cleaver-Yates Model

Chem. Eng. Sci. 30 (1975) 983.



Cleaver and Yates Model

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Flux

$$J = C(y) v_0(y) A_c(y)$$

Deposition Velocity

$$u_D^+ = \frac{J}{Cu^*} = \frac{v_0^+ A_c}{2}$$

Equation of Motion

$$A_c - capture\ area\ ratio = \frac{z_0}{\Lambda / 4}$$

$$\tau^+ \frac{dv^+}{dt^+} = v^{f+} - v^+$$

$$\tau^+ \frac{dw^+}{dt^+} = w^{f+} - w^+$$

Cleaver and Yates Model

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$$v^+ = v^{f+} - \tau^+ \left(v^{f+} \frac{\partial v^{f+}}{\partial y^+} + w^{f+} \frac{\partial v^{f+}}{\partial z^+} \right)$$

Perturbation Solution

$$w^+ = w^{f+} - \tau^+ \left(v^{f+} \frac{\partial w^{f+}}{\partial y^+} + w^{f+} \frac{\partial w^{f+}}{\partial z^+} \right)$$

Flow Field

$$w^f = \alpha z \varphi'(\eta)$$

$$v^f = -\sqrt{\alpha \nu}\, \varphi(\eta)$$

$$\eta = \sqrt{\frac{\alpha}{\nu}}\, y$$

$$\varphi''' + \varphi \varphi'' - \varphi'^2 + 1 = 0$$

Cleaver and Yates Model

Clarkson University

$$\alpha = 0.067\frac{u^{*2}}{\nu}$$ ⟺ $$y^+ = 10$$ $$v^{f+} = \frac{1}{2}$$

Boundary condition → $$y^+ = \frac{d^+}{2}$$ $$z^+ = 70$$ → $$A_c = \frac{z_0^+}{\Lambda^+ / 4}$$

Limiting Trajectory →

$$\ln\frac{z^+}{z_0} = \int_{\sqrt{\frac{\alpha\nu}{u^{*2}}}y_0^+}^{\sqrt{\frac{\alpha\nu}{u^{*2}}}y^+} \left\{\frac{\varphi' - \tau^+\left(\frac{\alpha\nu}{u^{*2}}\right)(\varphi'^2 - \varphi\varphi'')}{\varphi + \tau^+\left(\frac{d\nu}{u^{*2}}\right)\varphi\varphi'}\right\}dy$$

Cleaver and Yates Model

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Deposition Velocity

$$u_D^+ = \frac{9}{400}\frac{\rho^f}{\rho^p}\tau^+ \exp\{0.48\tau^+\}$$

$\tau^+ << 1$

$$u_D^+ = 0.45\exp\{-\frac{\tau}{0.9}\int_{d^+/2}^{\infty} 1 - \frac{f(y)}{0.9})dy\}$$

$\tau^+ >> 1$

To Account for Convection

$$u_D^+ |_{Actual} = 8.5 u_D^+$$

Deposition Velocity, Diffusion

$$u_D^+ = 0.084 S_c^{-2/3}$$

Minimum Deposition Velocity

$$\tau^+ S_c^{2/3} = 0.069\frac{\rho_p}{\rho_f}.$$

Fichman et al. Model

Clarkson University

Flow Field

$$U^+ = y^+$$

$$\left.\begin{aligned} &v^+ = B\phi = 0.625B^3y^{+2} \\ &\phi = 0.625\eta^2, \quad \eta = By^+, \qquad B = 0.271 \end{aligned}\right\} \text{for } y^+ \le 2$$

$$\left.\begin{aligned} &v^+ = c\phi = 0.24c - 0.71c^2y^+ \\ &\phi = 0.71\eta - 0.24, \qquad \eta = cy^+, \qquad c = 0.174 \end{aligned}\right\} \text{for } 2 \le y^+ \le 7$$

$$\left.\begin{aligned} &U^+ = 0.3y^+ + 0.5 \\ &v^+ = c\phi = 0.6c - c^2y^+, \; \phi = \eta - 0.6 \end{aligned}\right\} \text{for } 7 \le y^+ \le 30$$

Fichman et al. Model

Clarkson University

Deposition Velocity

$$u_D^+ = \frac{1}{2} A_c v_0^+$$

$$A_c = \frac{z_{lim}}{\Lambda / 4} = \frac{z_{lim}^+}{\Lambda^+ / 4}$$

$$u_D^+ = \frac{2 z_{lim}^+ v_0^+}{\Lambda^+}$$

Fichman et al. Model

Clarkson University

Equations of Motion

$$\tau^+ \frac{d^2x^+}{dt^{+2}} = U^+ - \frac{dx^+}{dt}$$

$$\tau^+ \frac{d^2y^+}{dt^{+2}} = v^+ - \frac{dy^+}{dt} + K\left(U^+ - \frac{dx^+}{dt}\right)$$

$$\tau^+ \frac{d^2z^+}{dt^{+2}} = w^+ - \frac{dz^+}{dt}$$

$$K = \tau^+ L^+$$

Lift

$$L^+ = \frac{L\nu}{u^{*2}}$$

Fichman et al. Model

Clarkson University

Lift

$$L \approx \frac{6.46\mu\left(\frac{d}{2}\right)^2}{\nu^{\frac{1}{2}} m_p}\left(\frac{dU}{dy}\right)^{\frac{1}{2}} = \frac{3.08\mu\dot{\gamma}^{\frac{1}{2}}}{\nu^{1/2} d\rho_p}$$

$$\dot{\gamma} = \frac{dU}{dy}$$

$$\frac{4z^{+}_{lim}}{\Lambda^{+}} = \frac{\frac{d^2}{4} + (d^{+} + s^{+})s^{+}}{4}$$

$$s^{+} \le 2$$

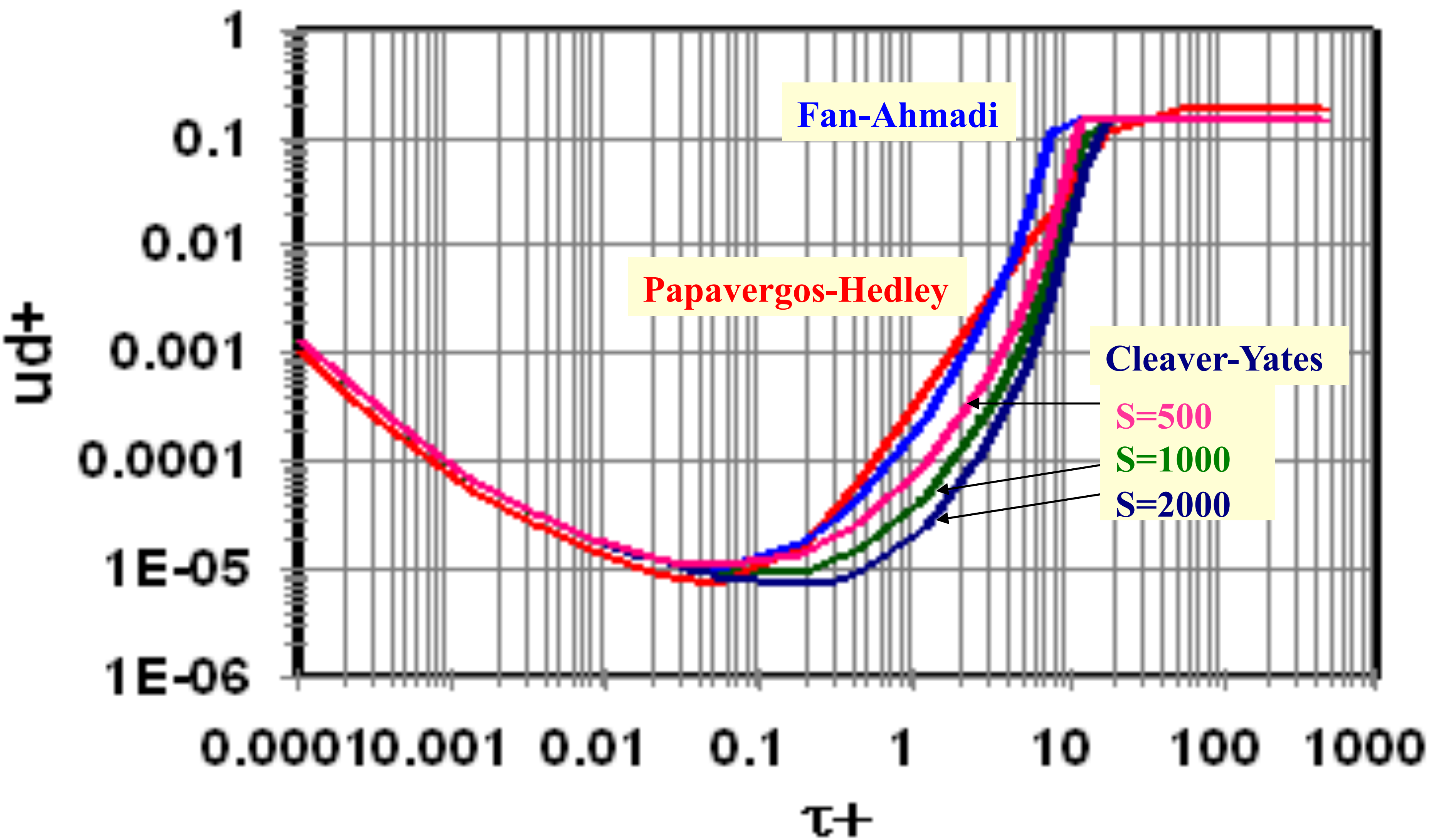
$$s^{+} = \frac{L^{+}\tau^{+2}(u^{+}_{po} - \dot{\gamma}^{+} y^{+}_{0}) + \tau^{+} v^{+}_{po}}{1 - \tau^{+2} L^{+} \dot{\gamma}^{+}}$$

Numerical Solution

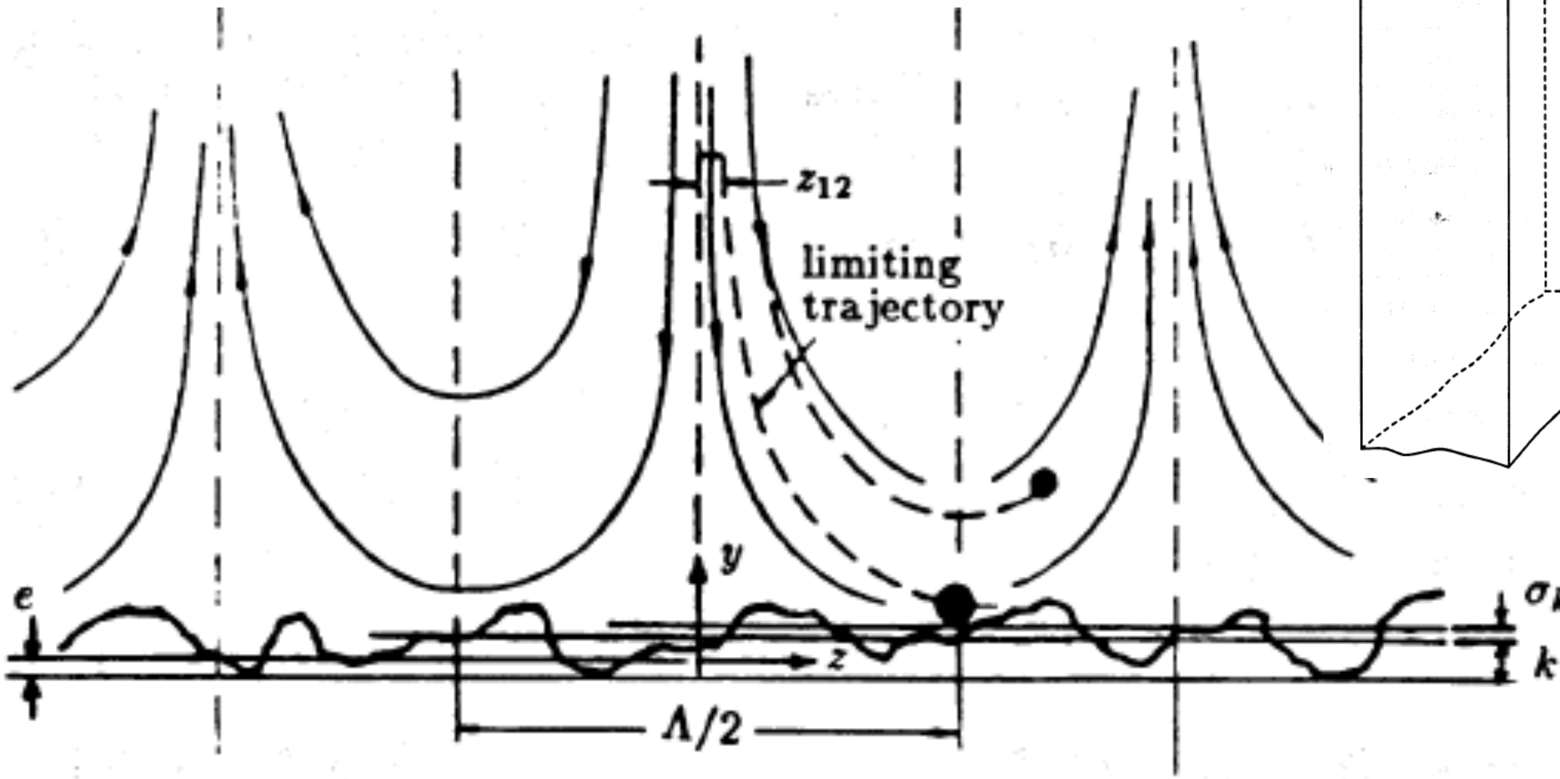
$$s^{+} \ge 2$$

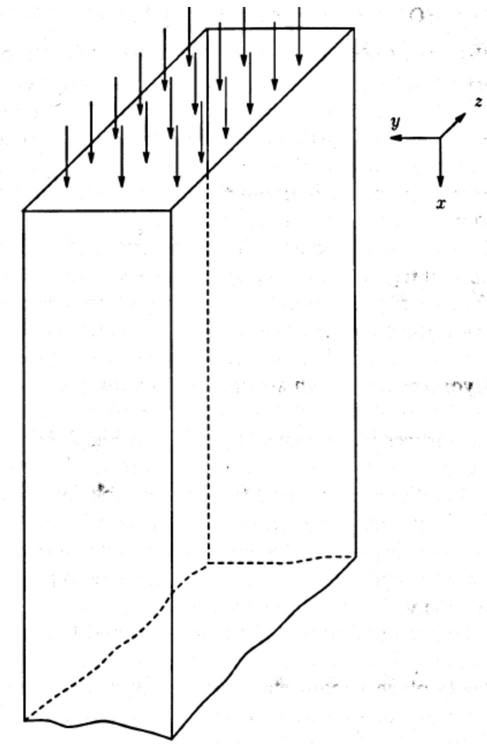
Cleaver and Yates Model

Clarkson University



Fan-Ahmadi Model





Fan-Ahmadi Model

Clarkson University

Equations of Motion

$$\tau^{+}\frac{\mathrm{d}u^{p+}}{\mathrm{d}t^{+}}=u^{+}-u^{p+}+\tau^{+}g^{+},$$

$$\tau^{+}\frac{\mathrm{d}v^{p+}}{\mathrm{d}t^{+}}=v^{+}-v^{p+}+\tau^{+}L_1^{+}(u^{+}-u^{p+})+\tau^{+}L_2^{+}(w^{+}-w^{p+}),$$

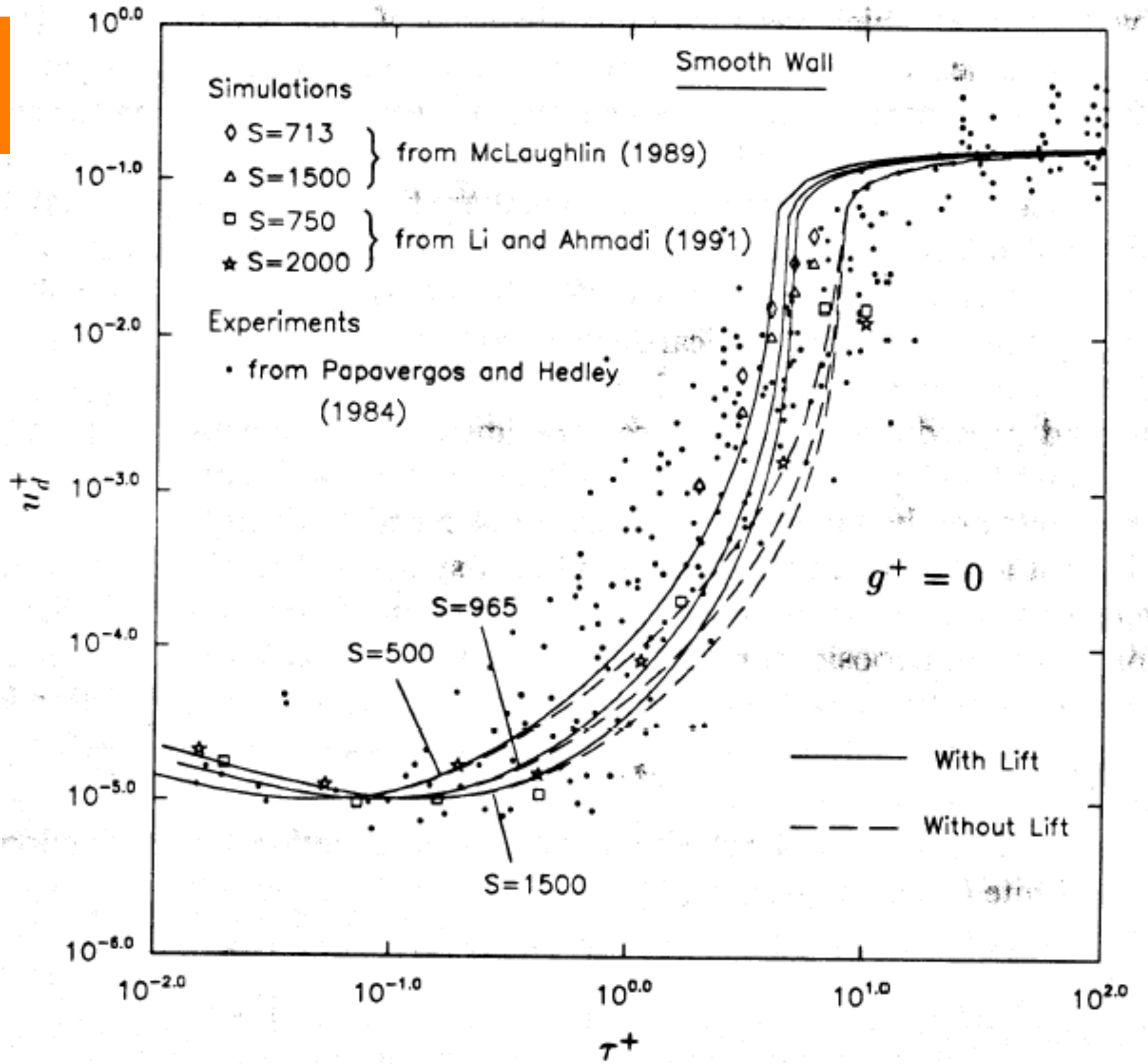
$$\tau^{+}\frac{\mathrm{d}w^{p+}}{\mathrm{d}t^{+}}=w^{+}-w^{p+},$$

Fan-Ahmadi Model

Clarkson University

Smooth Wall

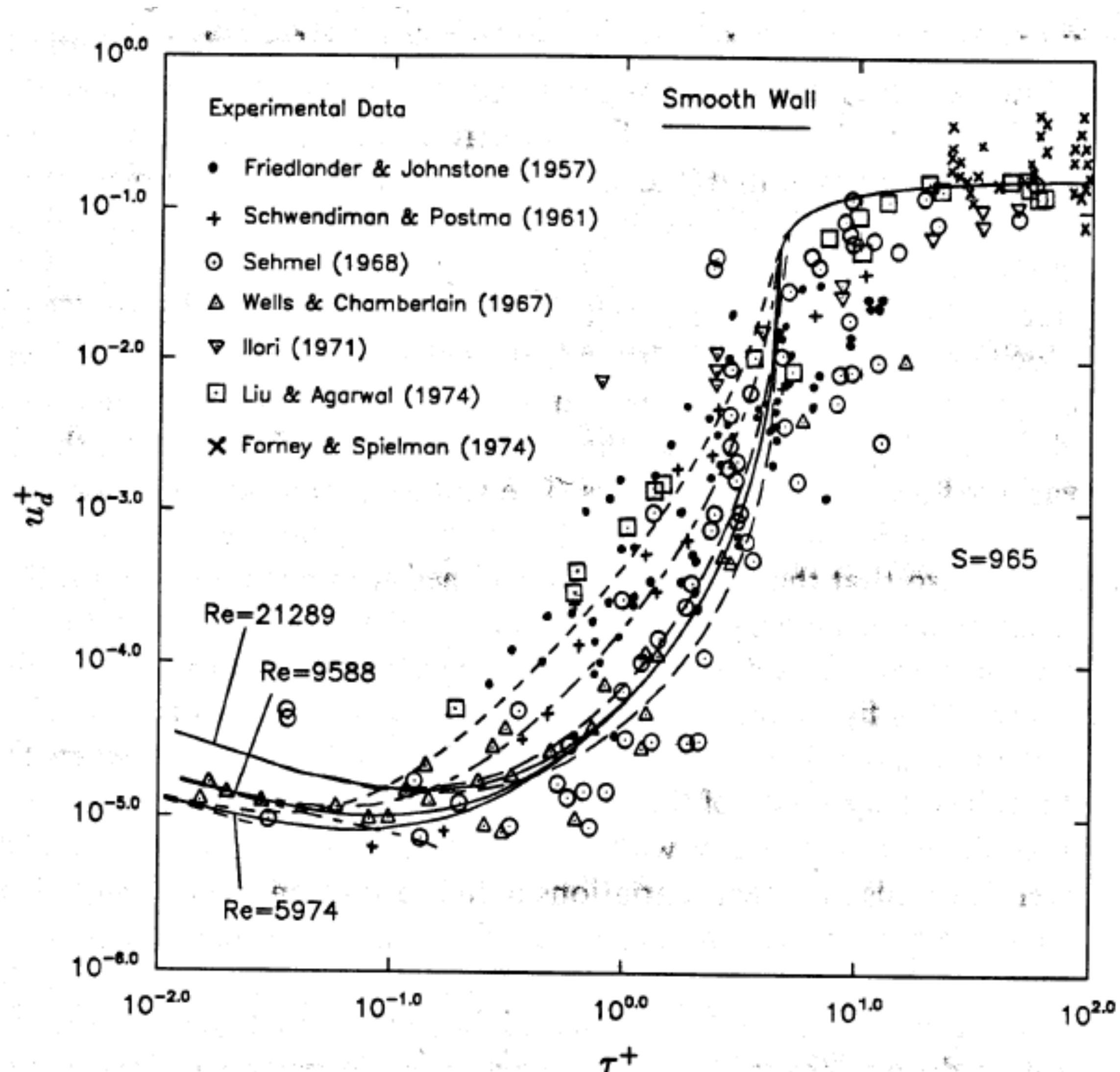
Comparison with Simulations



Fan-Ahmadi Model

Clarkson University

Smooth Wall



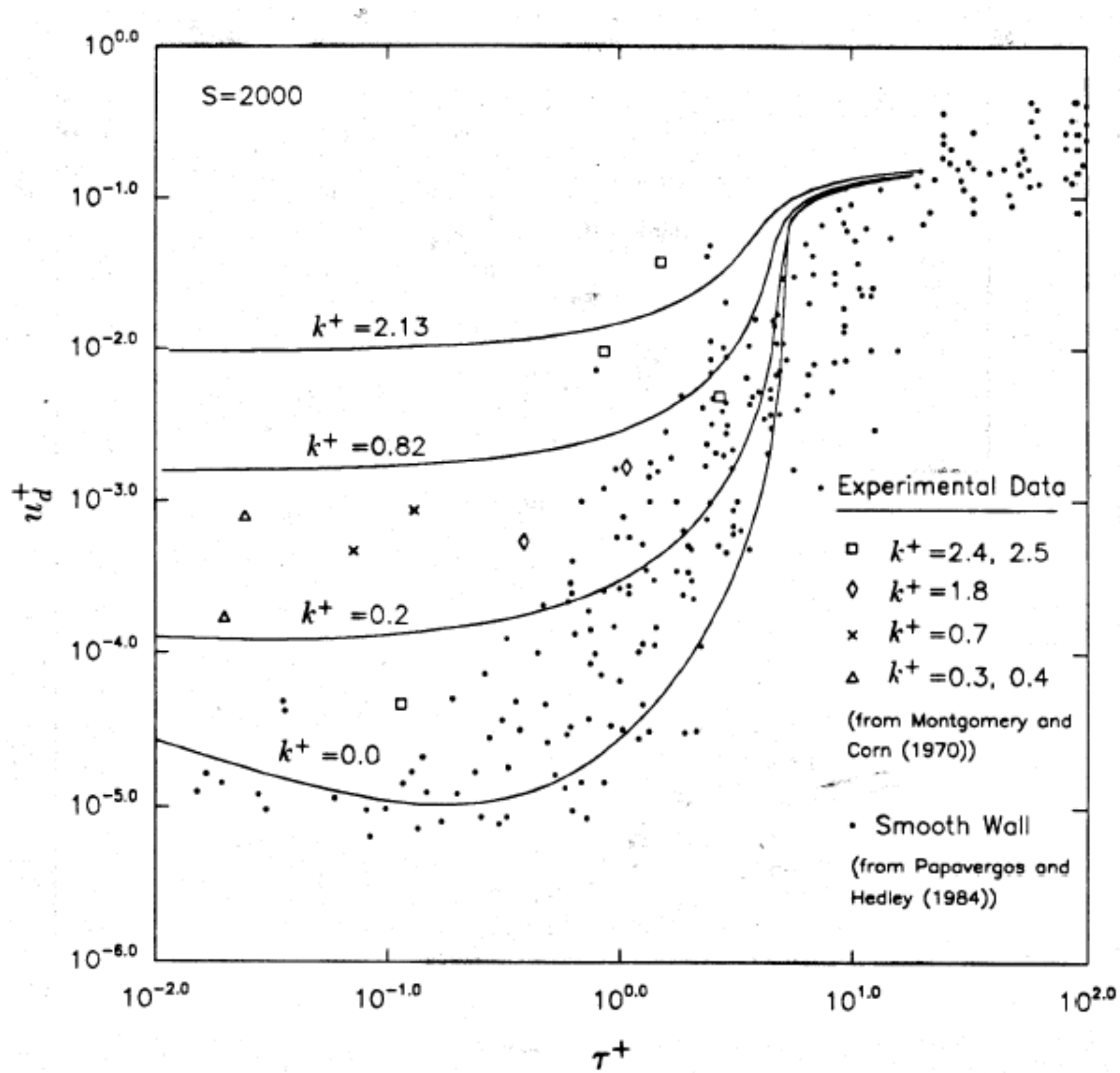
Comparison with Experiments

Fan-Ahmadi Model

Clarkson University

Rough Wall

Comparison with Experiments

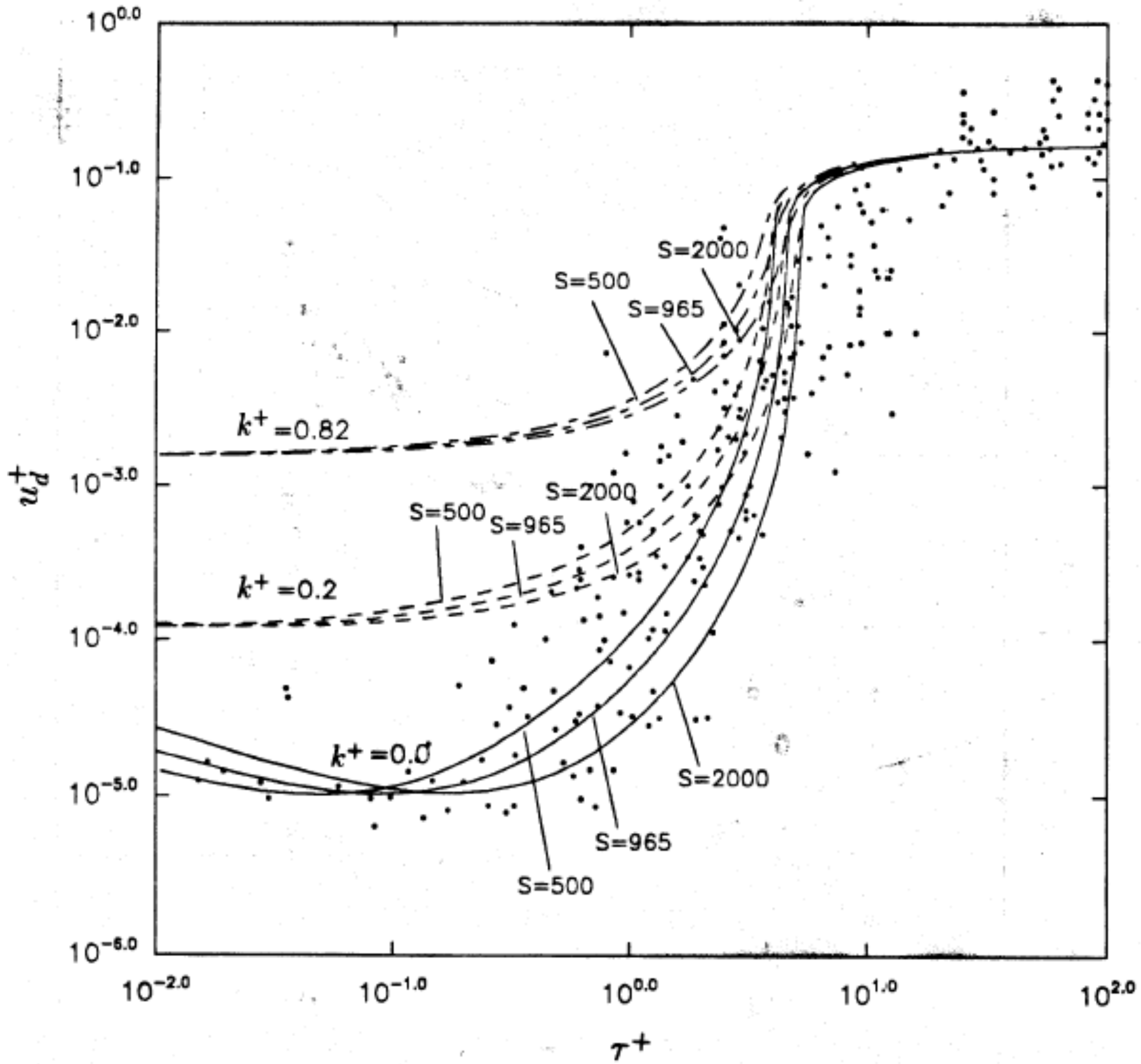


Fan-Ahmadi Model

Clarkson University

Rough Wall

Effects of Density Ratio



Deposition Velocity for Rough Walls

Clarkson University

Fan and Ahmadi

Empirical Model

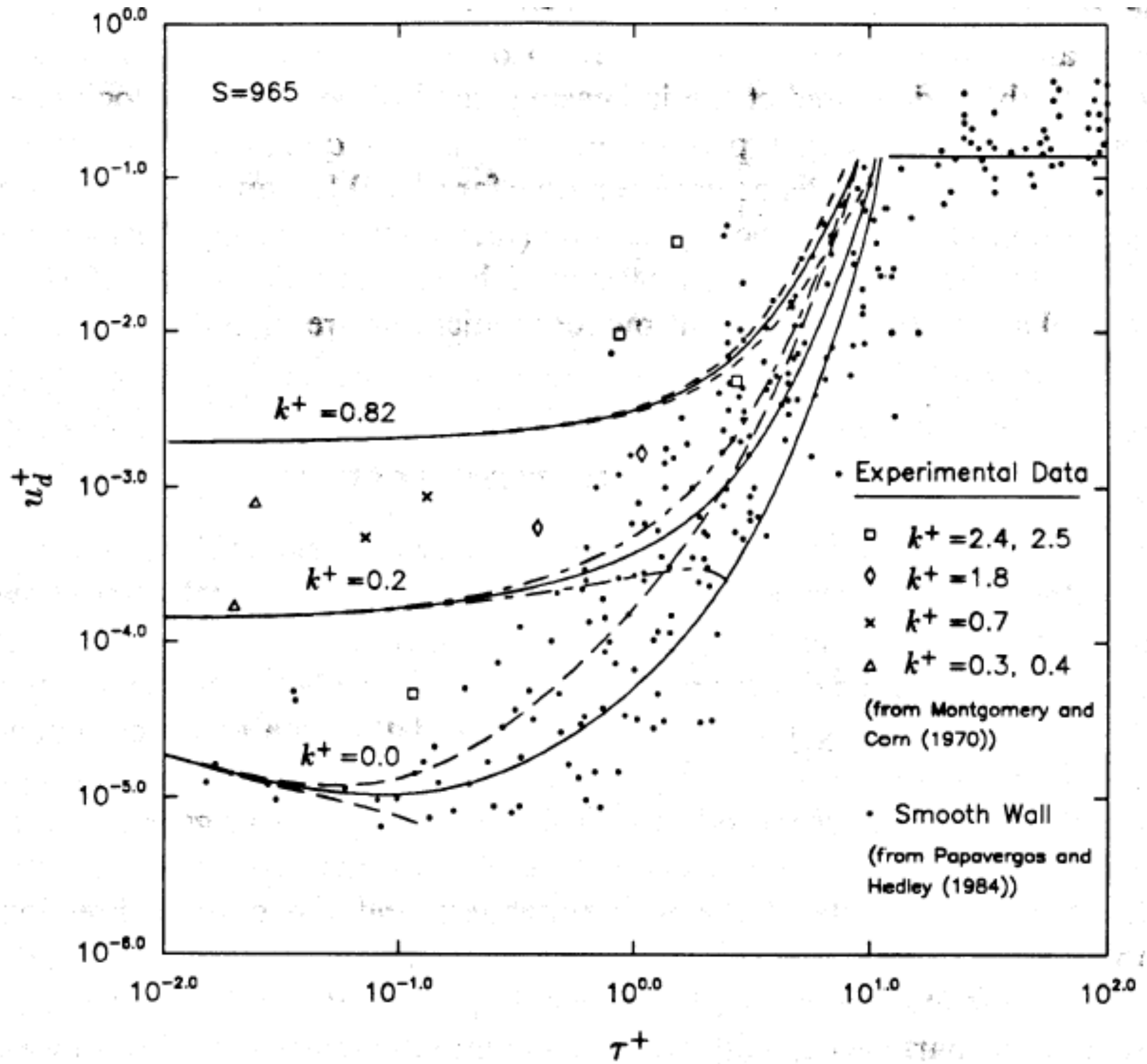
$$u_d^+ = \begin{cases} 0.084 Sc^{-2/3} + \dfrac{1}{2}\left[\dfrac{\left(0.64k^+ + \dfrac{d^+}{2}\right)^2 + \dfrac{\tau_p^{+2} g^+ L_1^+}{0.01085(1+\tau_p^{+2} L_1^+)}}{3.42 + \dfrac{\tau_p^{+2} g^+ L_1^+}{0.01085(1+\tau_p^{+2} L_1^+)}}\right]^{1/\left(1+\tau_p^{+2} L_1^+\right)} & \\ \times\left[1 + 8e^{-(\tau_p^+ - 10)^2/32}\right]\dfrac{0.037}{1-\tau_p^{+2} L_1^+ \left(1+\dfrac{g^+}{0.037}\right)} & \text{if } u_d^+ < 0.14 \\ 0.14 & \text{otherwise} \end{cases}$$

Fan-Ahmadi Model

Clarkson University

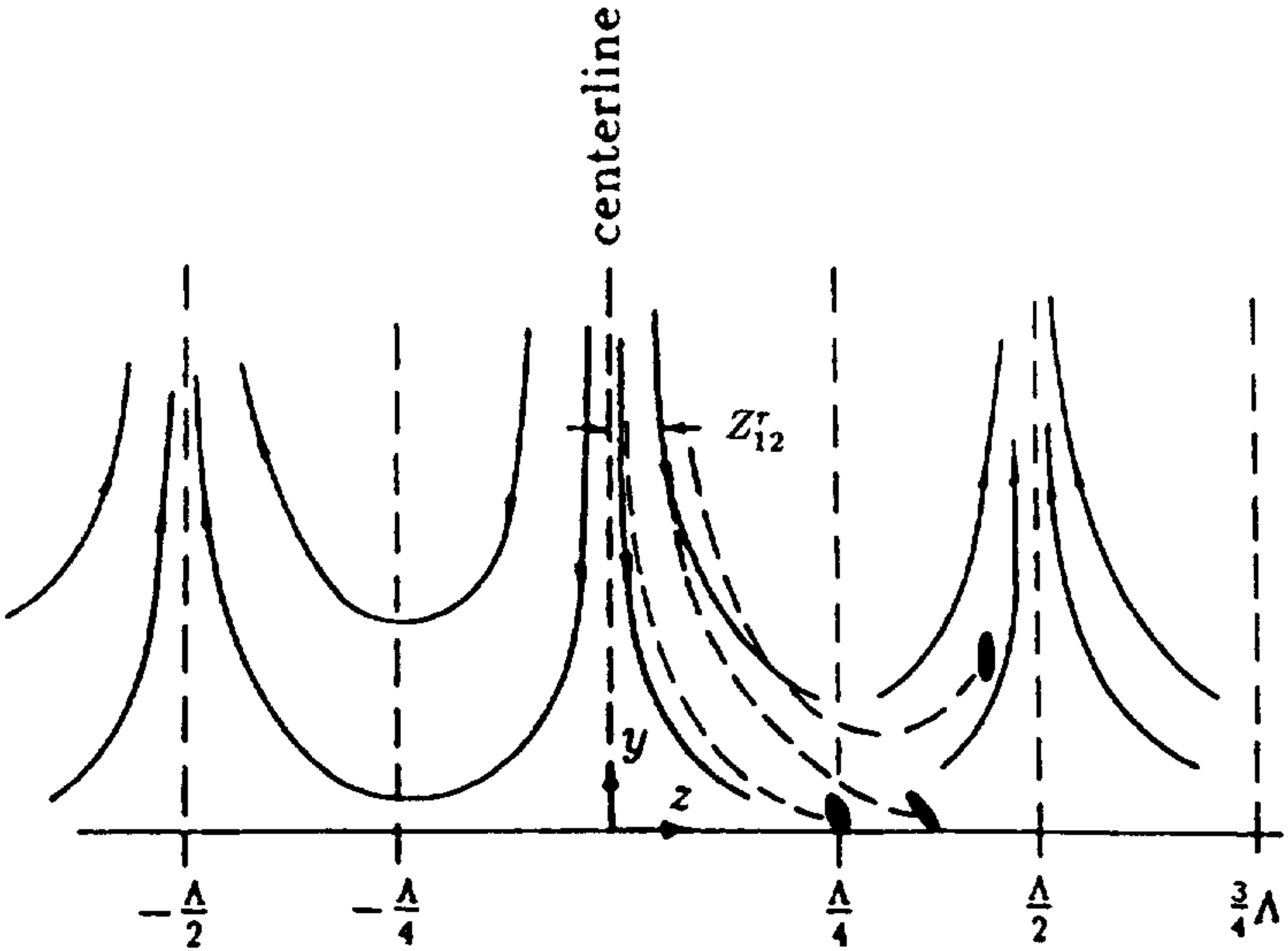
Rough Wall

Empirical Model Predictions



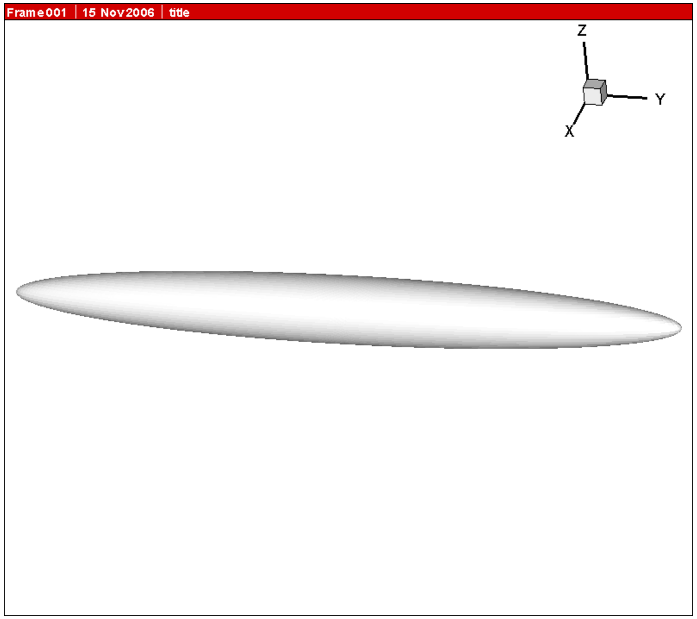
Sublayer Model For Fiber Deposition

Clarkson University



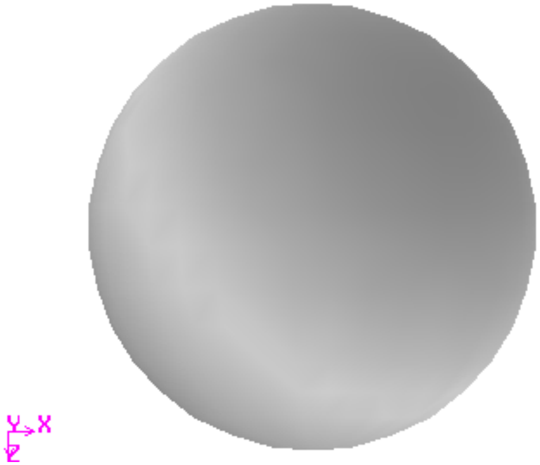
Fiber Geometric Model

Clarkson University



Ellipsoidal fiber particles

- Non-isometric
- Non-Isotropic behavior
- Orientation dependent



Spherical particles

- Isometric
- Isotropic property
- Orientation independent

Fiber Equation of Motion

Clarkson University

Translational Motion

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

Rotational Motion

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

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

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

Fiber Equation of Motion

Drag

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

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

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

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

Equivalent Relaxation Time Shapiro-Goldenberg

$$\tau_{eq}^{+} = \frac{4\beta Sa^{+2}}{9}\left(\frac{1}{k_{\hat{x}\hat{x}}}+\frac{1}{k_{\hat{y}\hat{y}}}+\frac{1}{k_{\hat{z}\hat{z}}}\right) = \frac{2\beta Sa^{+2}}{9}\,\frac{\ln\left(\beta+\sqrt{\beta^2-1}\right)}{\sqrt{\beta^2-1}}$$

Fiber Equation of Motion

Clarkson University

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

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

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

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

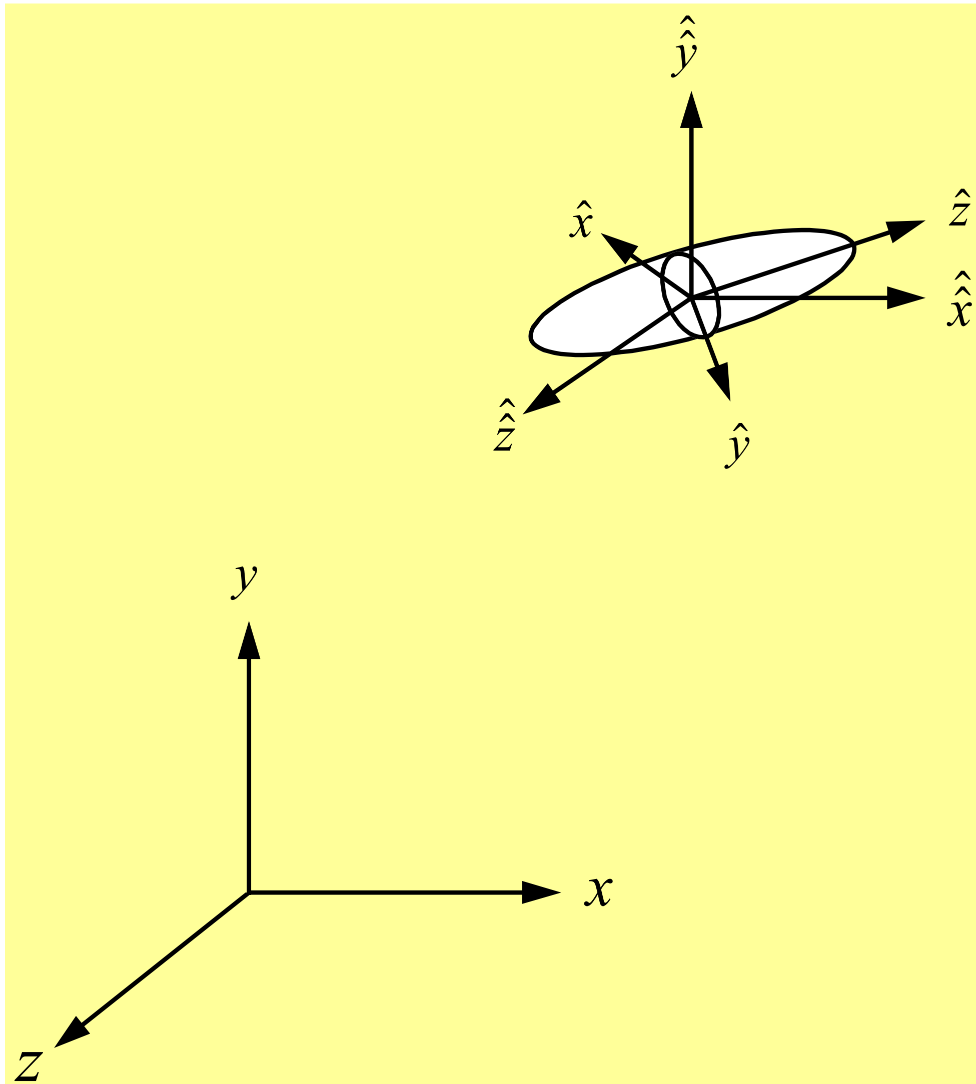
Fiber Shear Lift

Clarkson University

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

$$\mathbf{L} = \begin{bmatrix} 0.0501 & 0.0329 & 0.00 \\ 0.0182 & 0.0173 & 0.00 \\ 0.00 & 0.00 & 0.0373 \end{bmatrix}$$

Schematics of Ellipsoidal Fiber



Transformation Matrix and Euler Parameters

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Euler Angles

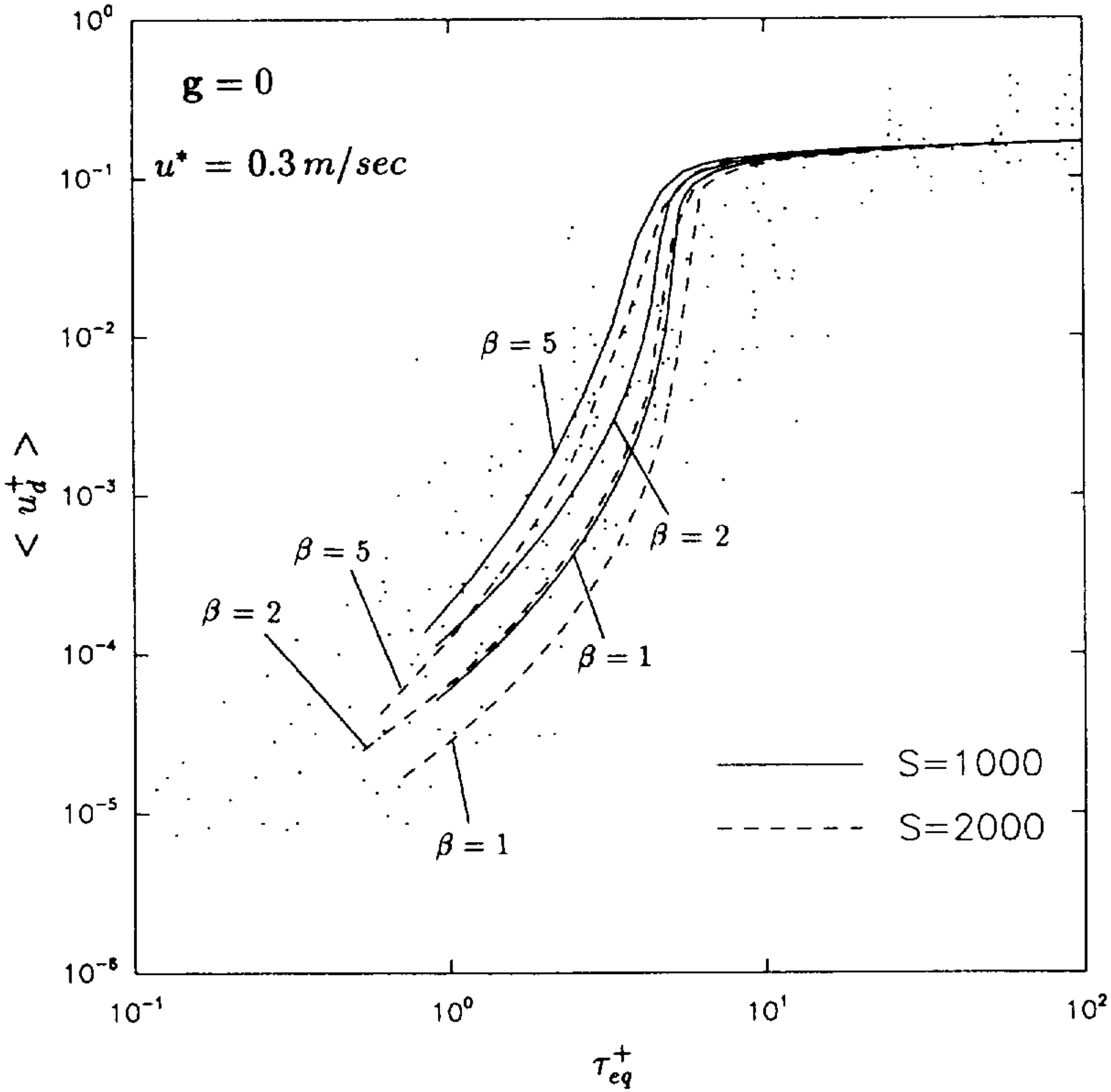
$$\mathbf{A} = \begin{bmatrix} \cos\psi\cos\phi - \cos\theta\sin\phi\sin\psi & \cos\psi\sin\phi + \cos\theta\cos\phi\sin\psi & \sin\psi\sin\theta \\ -\sin\psi\cos\phi - \cos\theta\sin\phi\cos\psi & -\sin\psi\sin\phi + \cos\theta\cos\phi\cos\psi & \cos\psi\sin\theta \\ \sin\theta\sin\phi & -\sin\theta\cos\phi & \cos\theta \end{bmatrix}$$

Euler Parameters

$$\mathbf{A} = \begin{bmatrix} 1 - 2\left(\varepsilon_2^2 + \varepsilon_3^2\right) & 2\left(\varepsilon_1\varepsilon_2 + \varepsilon_3\eta\right) & 2\left(\varepsilon_1\varepsilon_3 - \varepsilon_2\eta\right) \\ 2\left(\varepsilon_2\varepsilon_1 - \varepsilon_3\eta\right) & 1 - 2\left(\varepsilon_3^2 + \varepsilon_1^2\right) & 2\left(\varepsilon_2\varepsilon_3 + \varepsilon_1\eta\right) \\ 2\left(\varepsilon_3\varepsilon_1 + \varepsilon_2\eta\right) & 2\left(\varepsilon_3\varepsilon_2 - \varepsilon_1\eta\right) & 1 - 2\left(\varepsilon_1^2 + \varepsilon_2^2\right) \end{bmatrix}$$

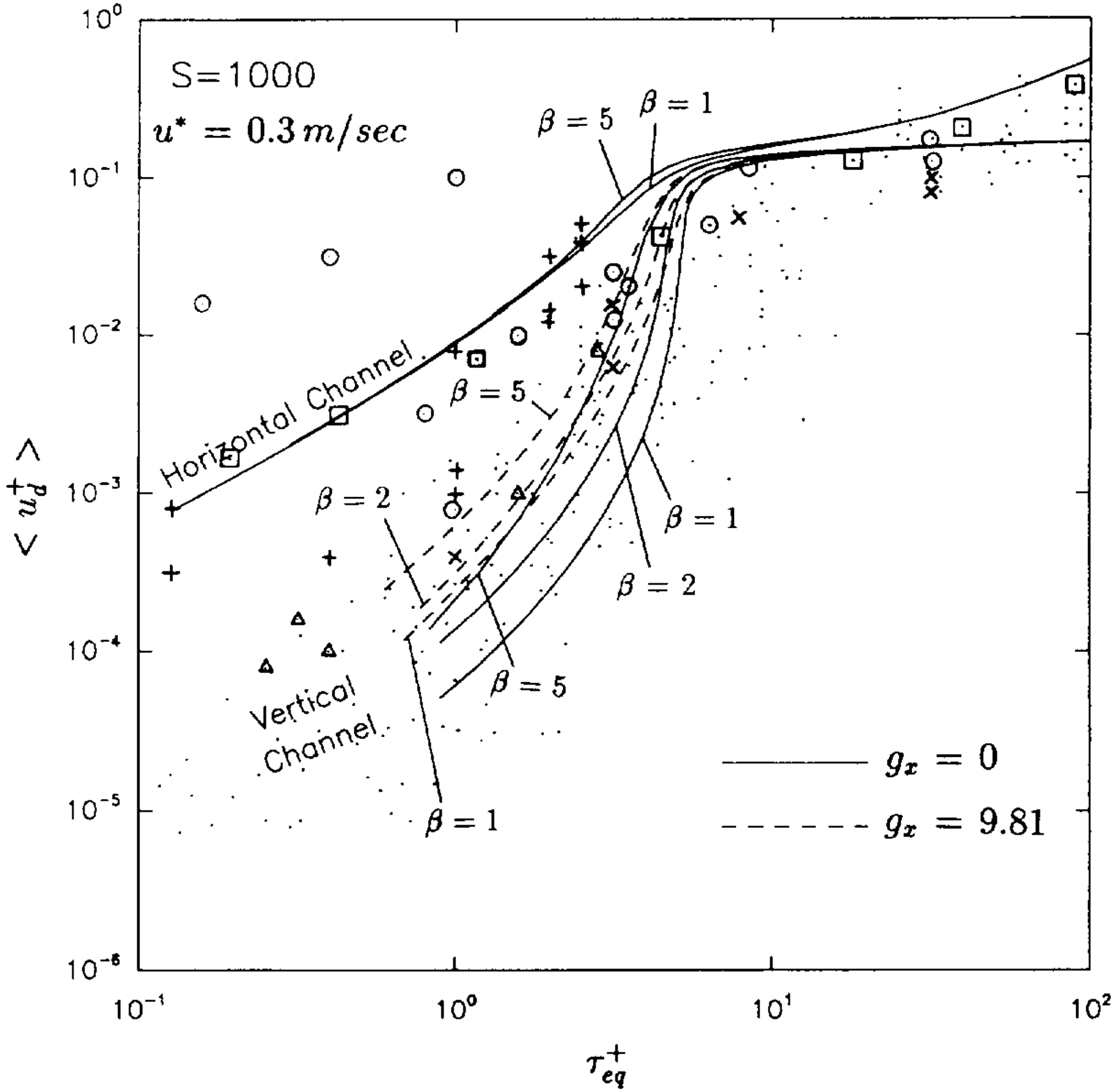
$$\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^3 + \eta^2 = 1$$

Fiber Depositing Velocity



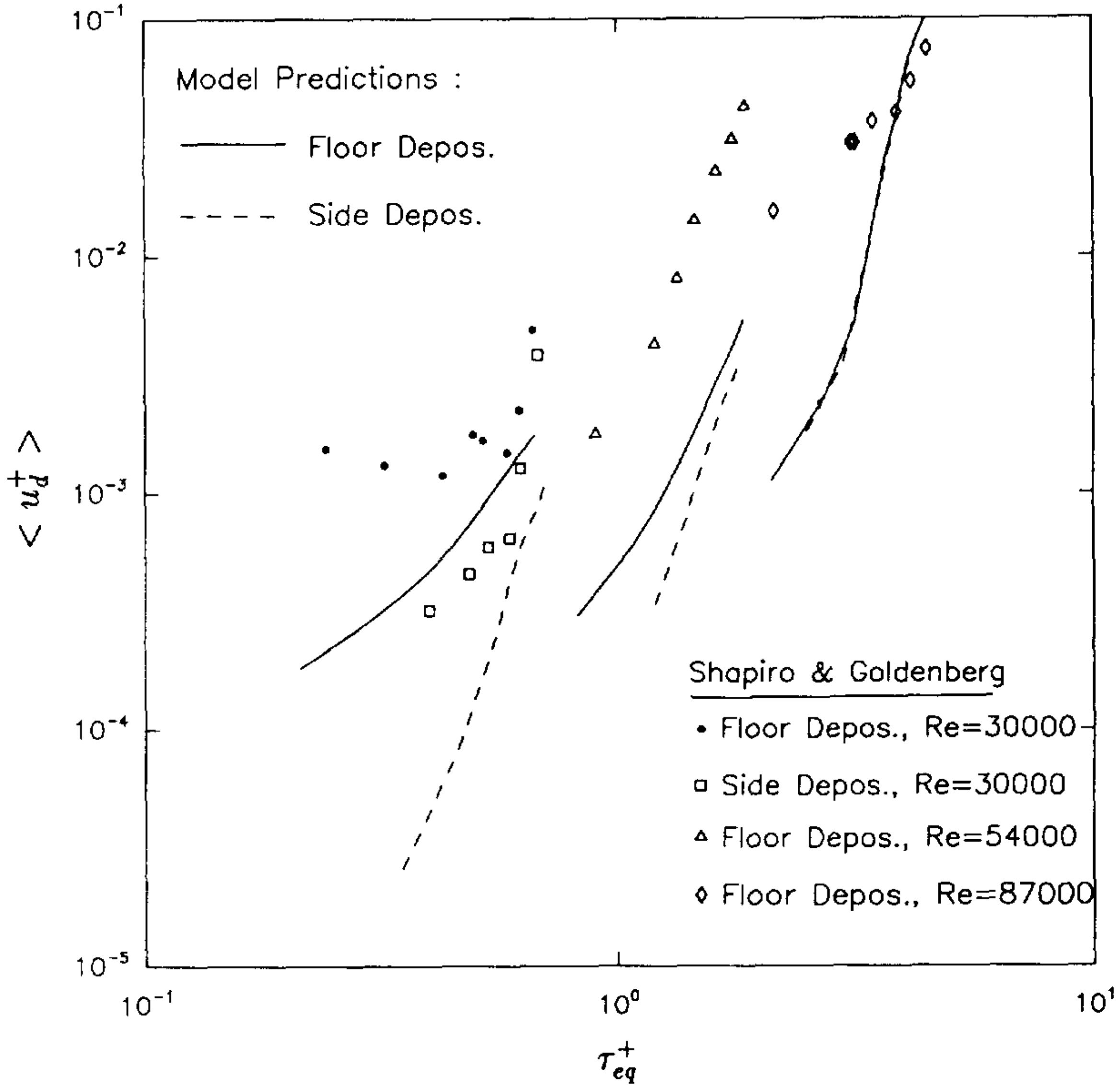
Fiber Depositing Velocity

Clarkson University



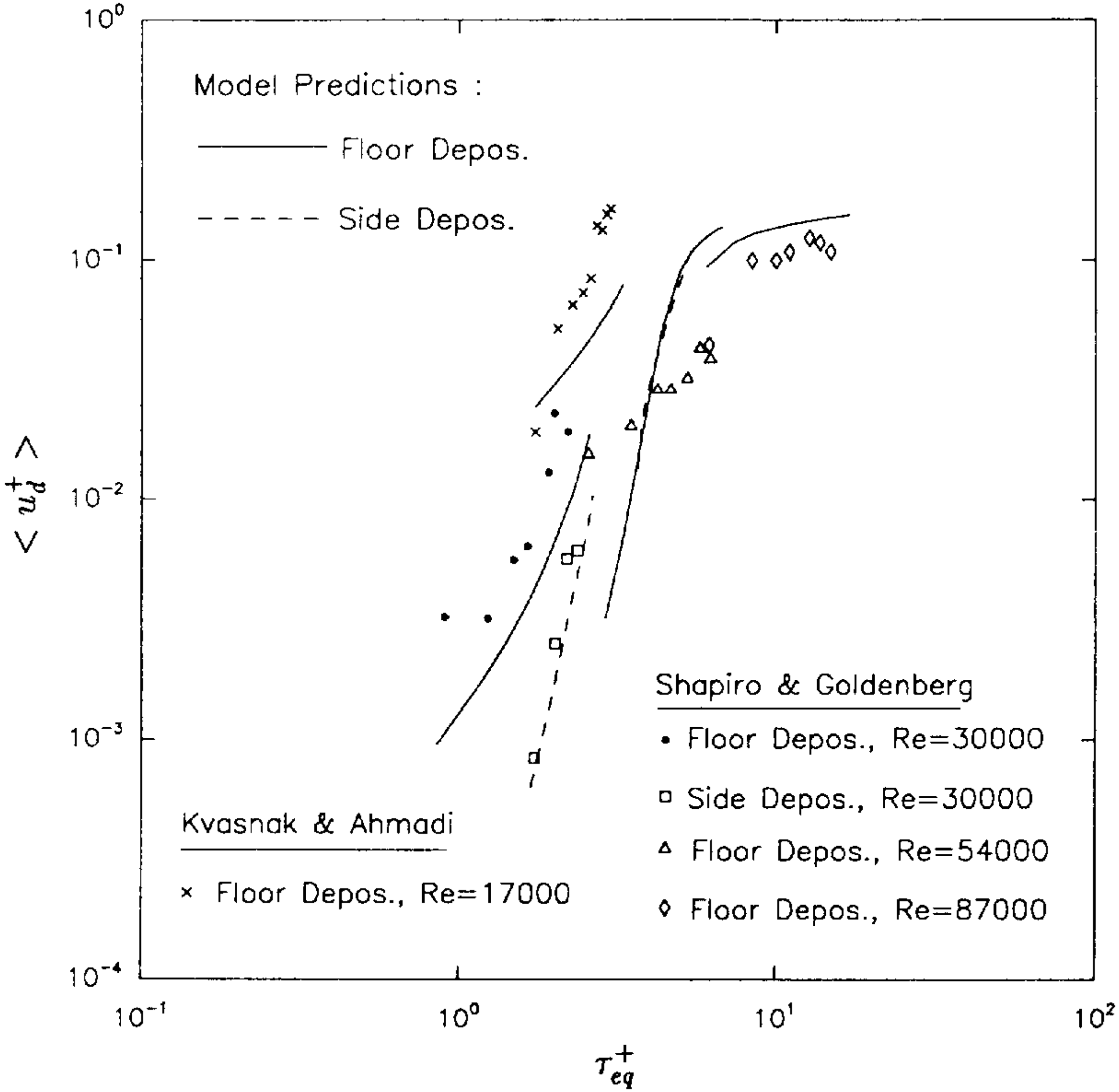
Fiber Depositing Velocity - Comparison with Experiment

Clarkson University

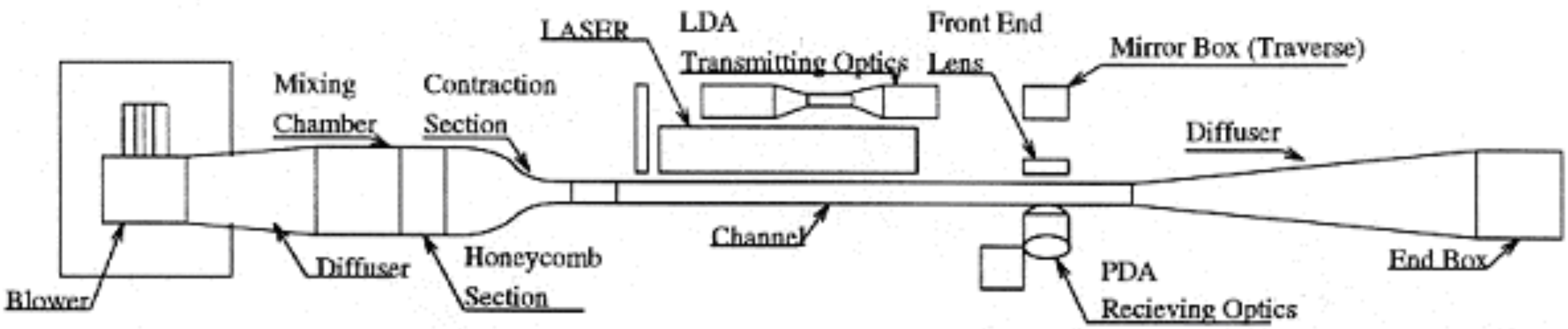


Fiber Depositing Velocity - Comparison with Experiment

Clarkson University

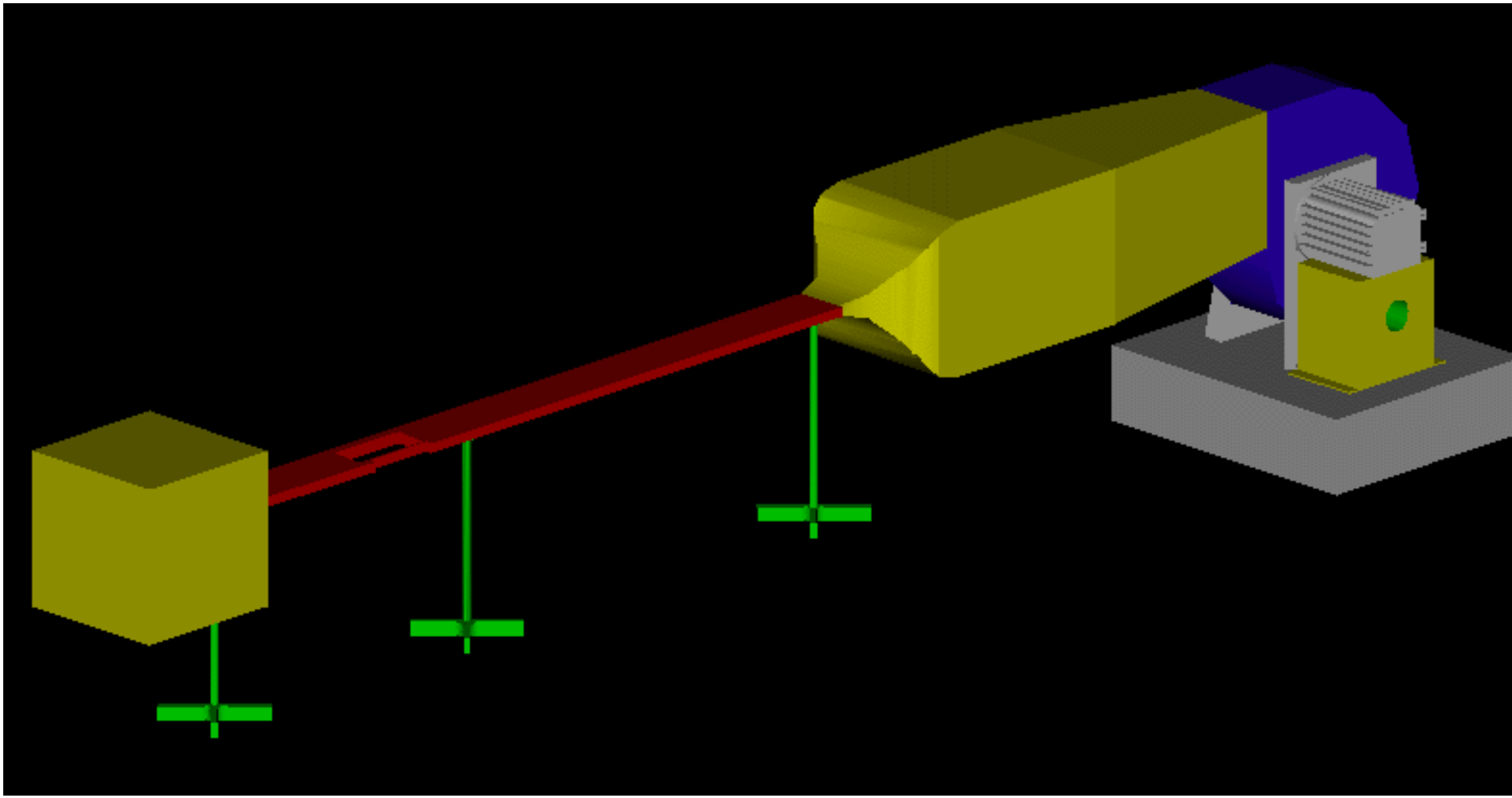


Experimental Fiber Deposition



Experimental Fiber Deposition

Clarkson University



Aerosol Wind Tunnel

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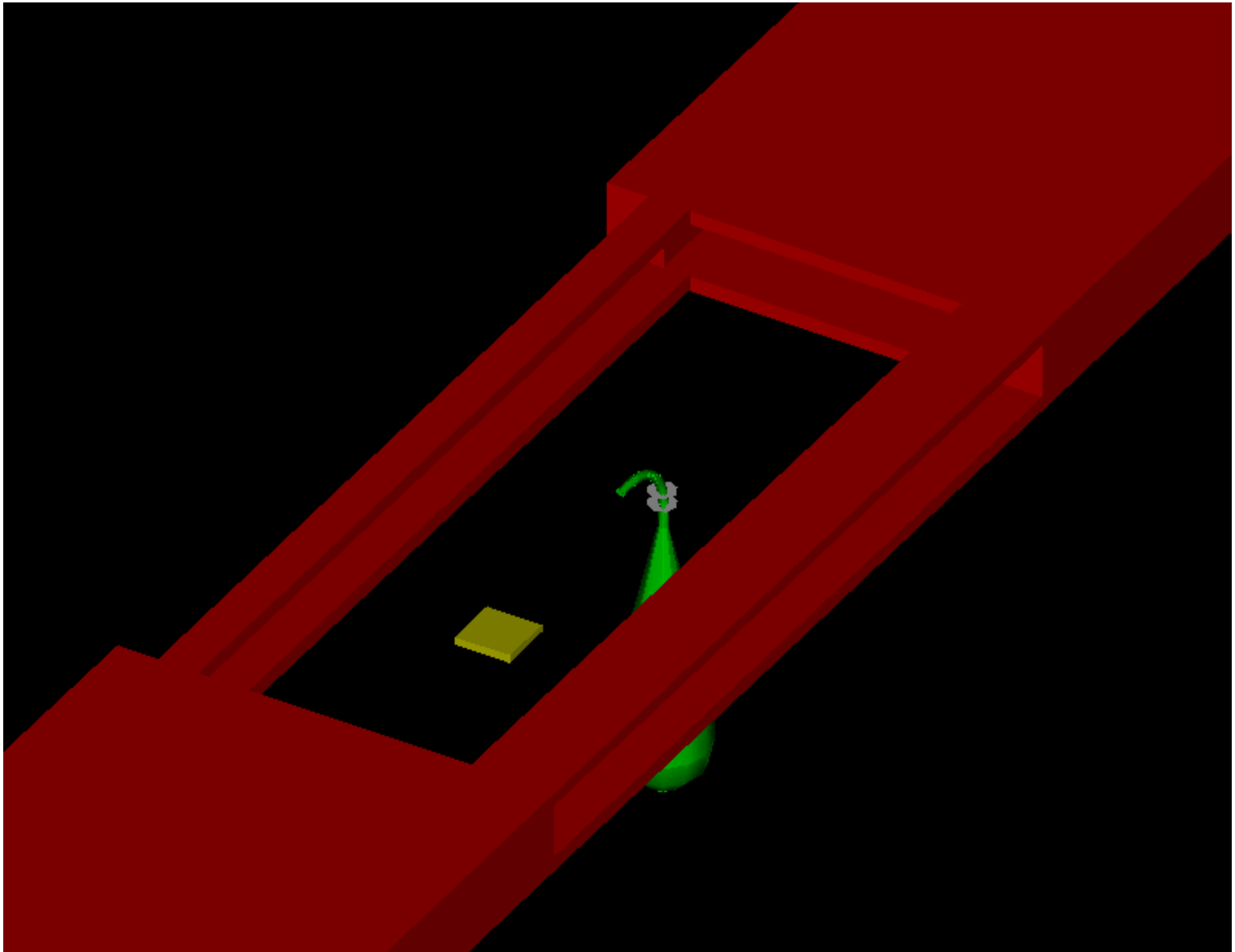
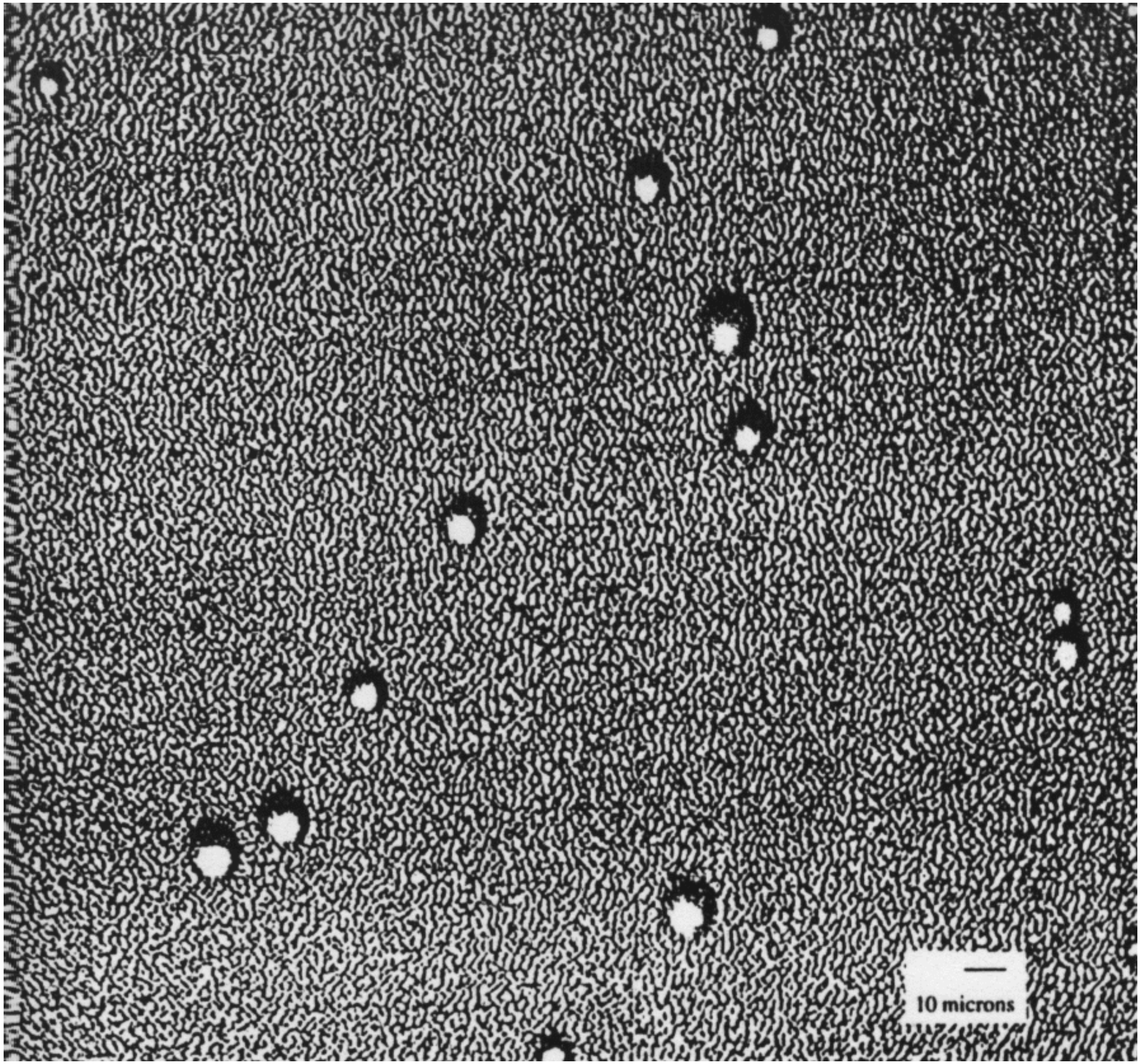
Test Section of Aerosol Wind Tunnel

Clarkson University



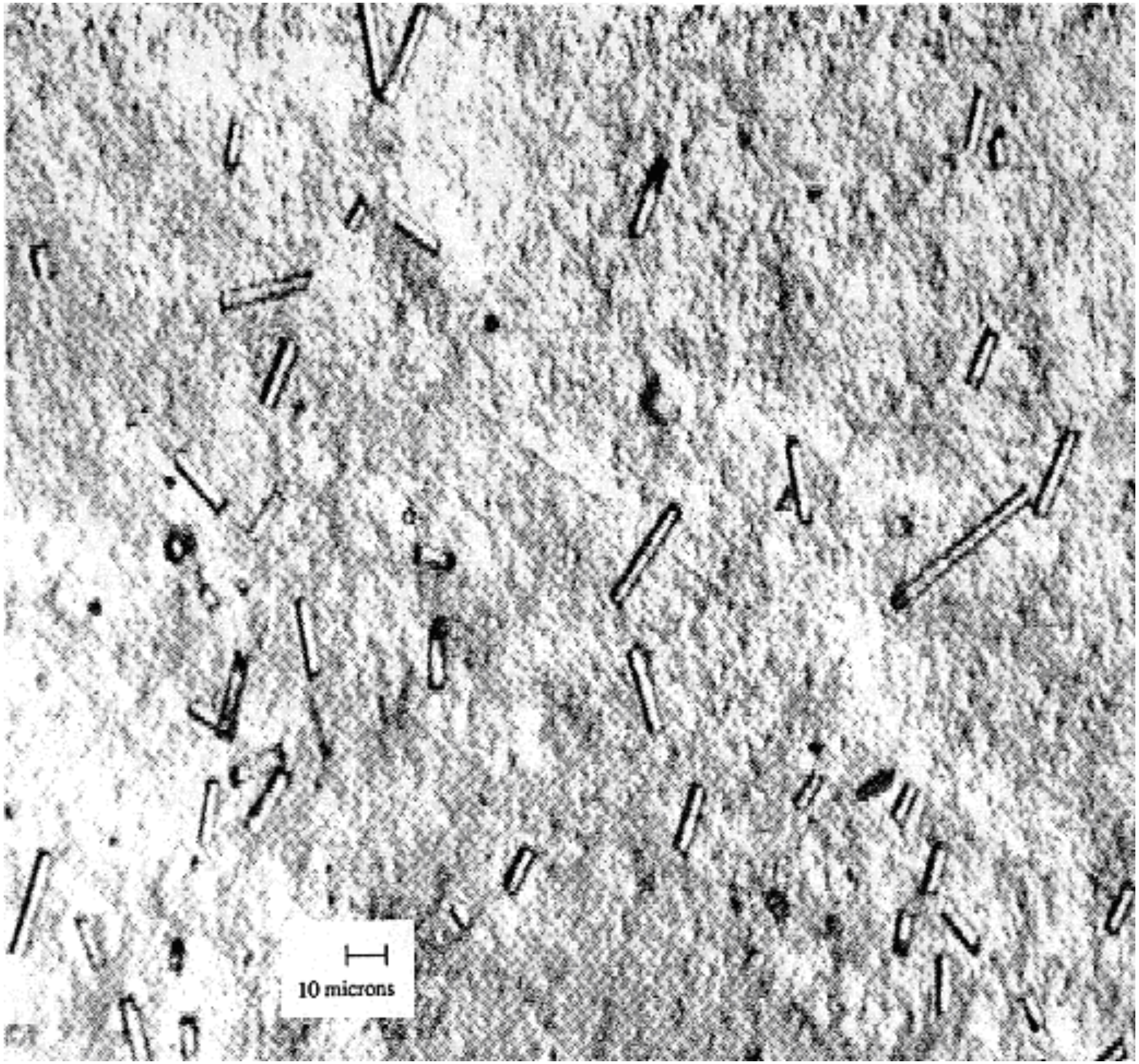
Deposited Glass Spheres

Clarkson University



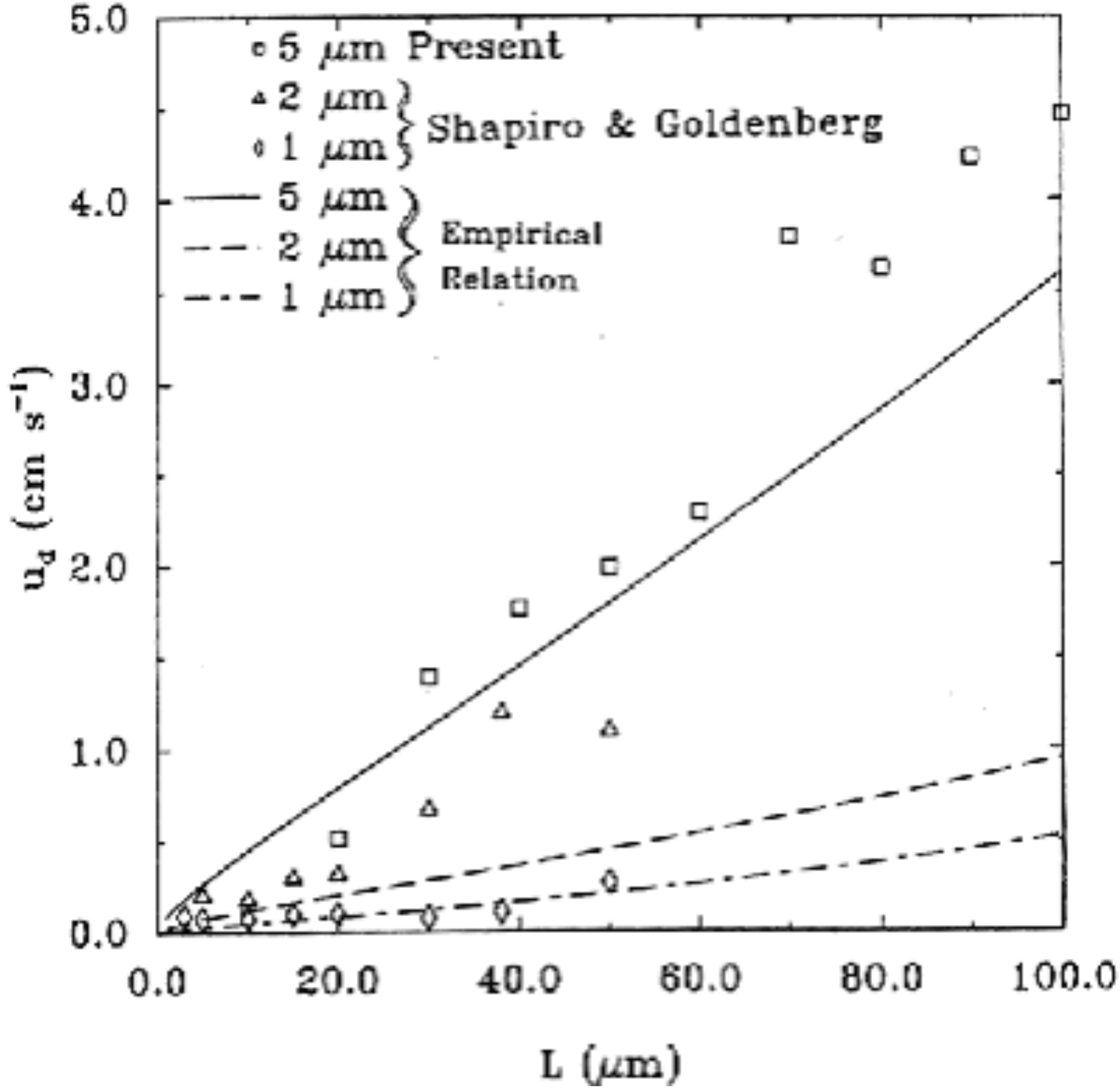
Deposited Glass Fibers

Clarkson University



Comparison of Fibers Deposition Rates

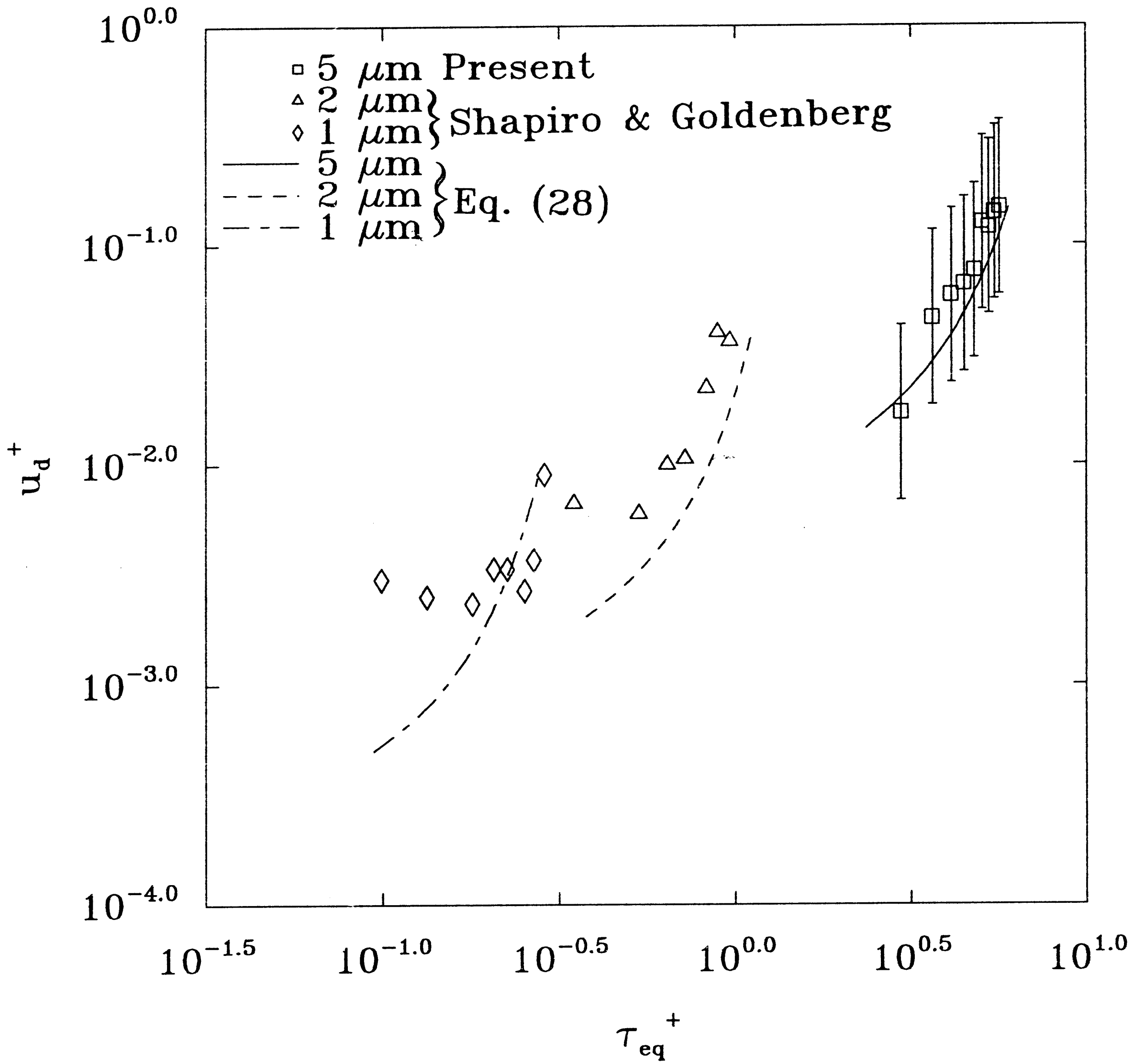
Clarkson University



Experimental Fiber Deposition Rates

Clarkson University

Glass Fibers



Flexible String

Clarkson University

Governing Equations

$$\frac{\partial v_i}{\partial t} = \frac{1}{A\rho_p}\left[f_i + \frac{\partial}{\partial s}\left(F\frac{\partial x_i}{\partial s}\right)\right], \qquad \frac{\partial x_i}{\partial t} = v_i$$

$$\mathrm{f}_\mathrm{i} = \frac{2\pi\mu}{\ln(2\beta)}\left[\left(2\delta_{ij} - \frac{\partial x_i}{\partial s}\frac{\partial x_j}{\partial s}\right)(u_j - v_j)\right]$$

Flexible String

Clarkson University

$$\frac{\partial^2 F}{\partial s^2} - F\frac{\partial^2 x_i}{\partial s^2}\frac{\partial^2 x_i}{\partial s^2} = -\left(\frac{\partial f_i}{\partial s}\frac{\partial x_i}{\partial s} + A\rho_p\frac{\partial v_i}{\partial s}\frac{\partial v_i}{\partial s}\right)$$

$$\frac{\partial \mathrm{f}_i}{\partial \mathrm{s}}\frac{\partial \mathrm{x}_i}{\partial \mathrm{s}} = \frac{2\pi\mu}{\ln(2\beta)}\left(\frac{\partial \mathrm{u}_i}{\partial \mathrm{s}}\frac{\partial \mathrm{x}_i}{\partial \mathrm{s}} - \frac{\partial \mathrm{x}_i^{\,2}}{\partial \mathrm{s}^2}(\mathrm{u}_i - \mathrm{v}_i)\right)$$

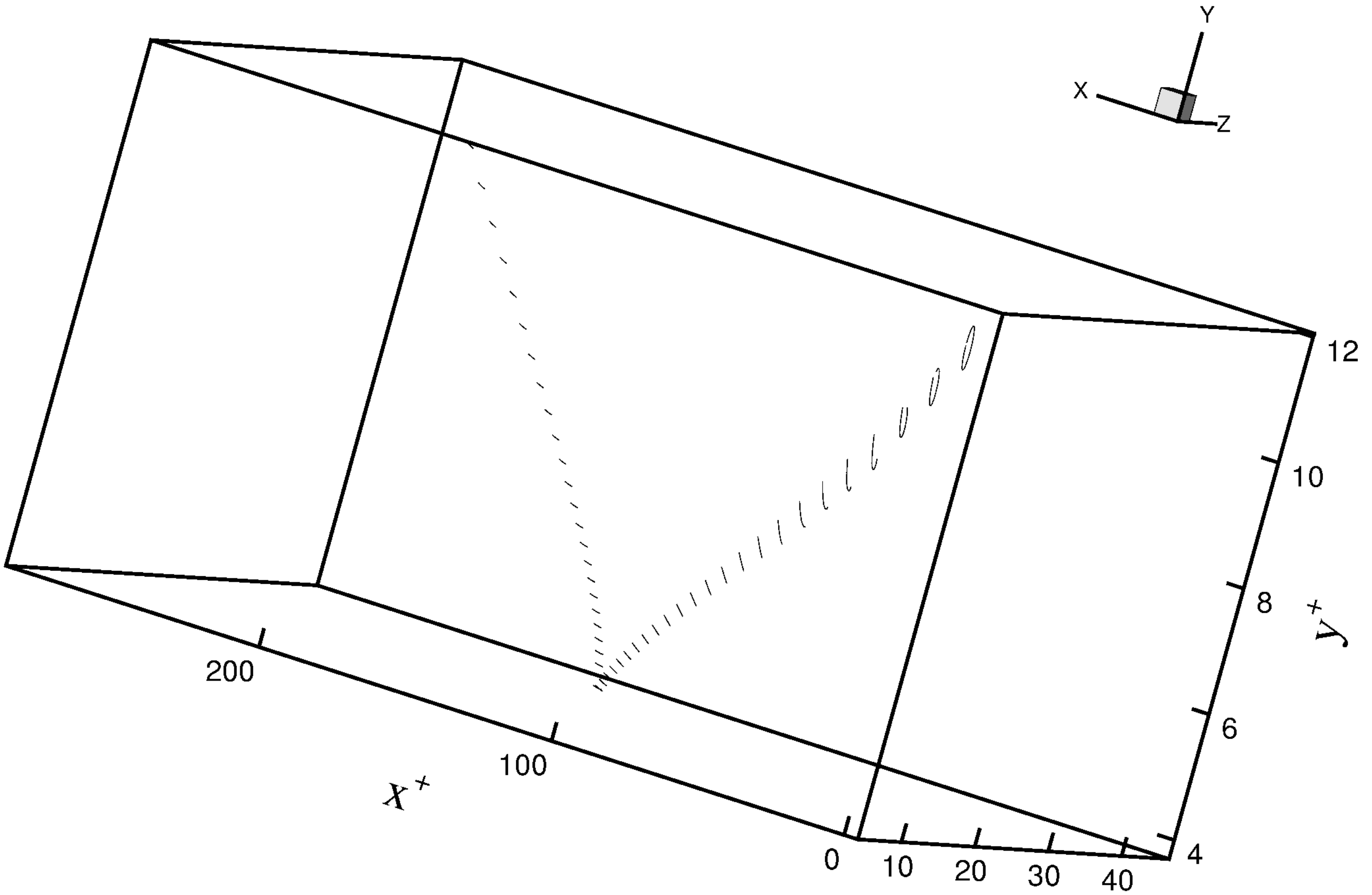
Flexible String

Clarkson University

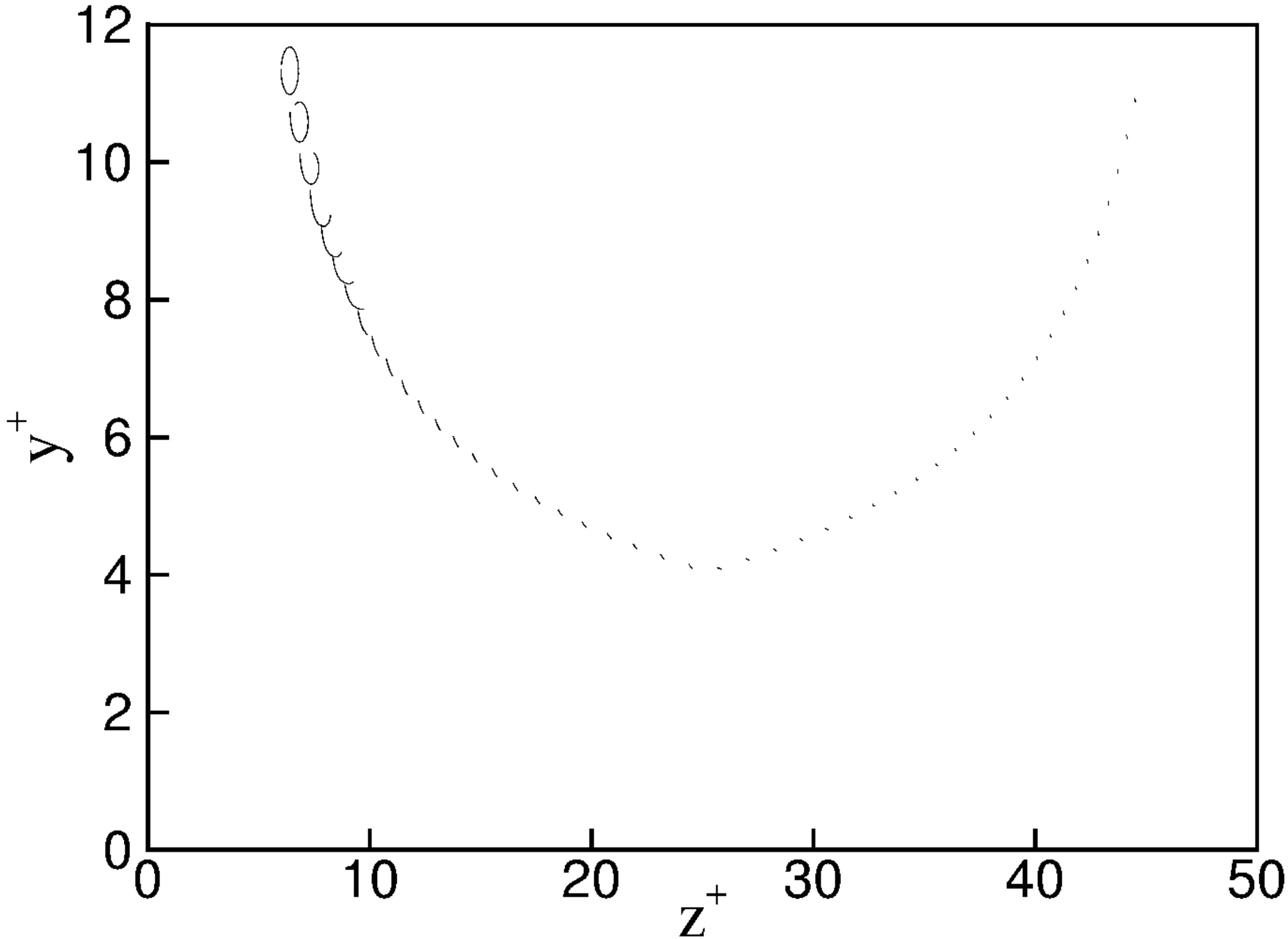
Empirical Equation for Flexible String Deposition

$$u_d^+ = \begin{cases} 0.0234 \times \left[\dfrac{\beta L^{+2}}{\ln(\beta) + 3} + \dfrac{0.9 e^{0.018\tau_d^+}}{(\ln(\beta) + 1) e^{(\tau_d^+ - 1)^3}} \right] \\ \times \left[\dfrac{1 + 10 e^{-(\tau_d{}^+ - 13)^2 / 32}}{0.049\beta^{2.5} + 10} \right] & if\ u_d^+ < 0.14 \\ 0.14 & otherwise \end{cases}$$

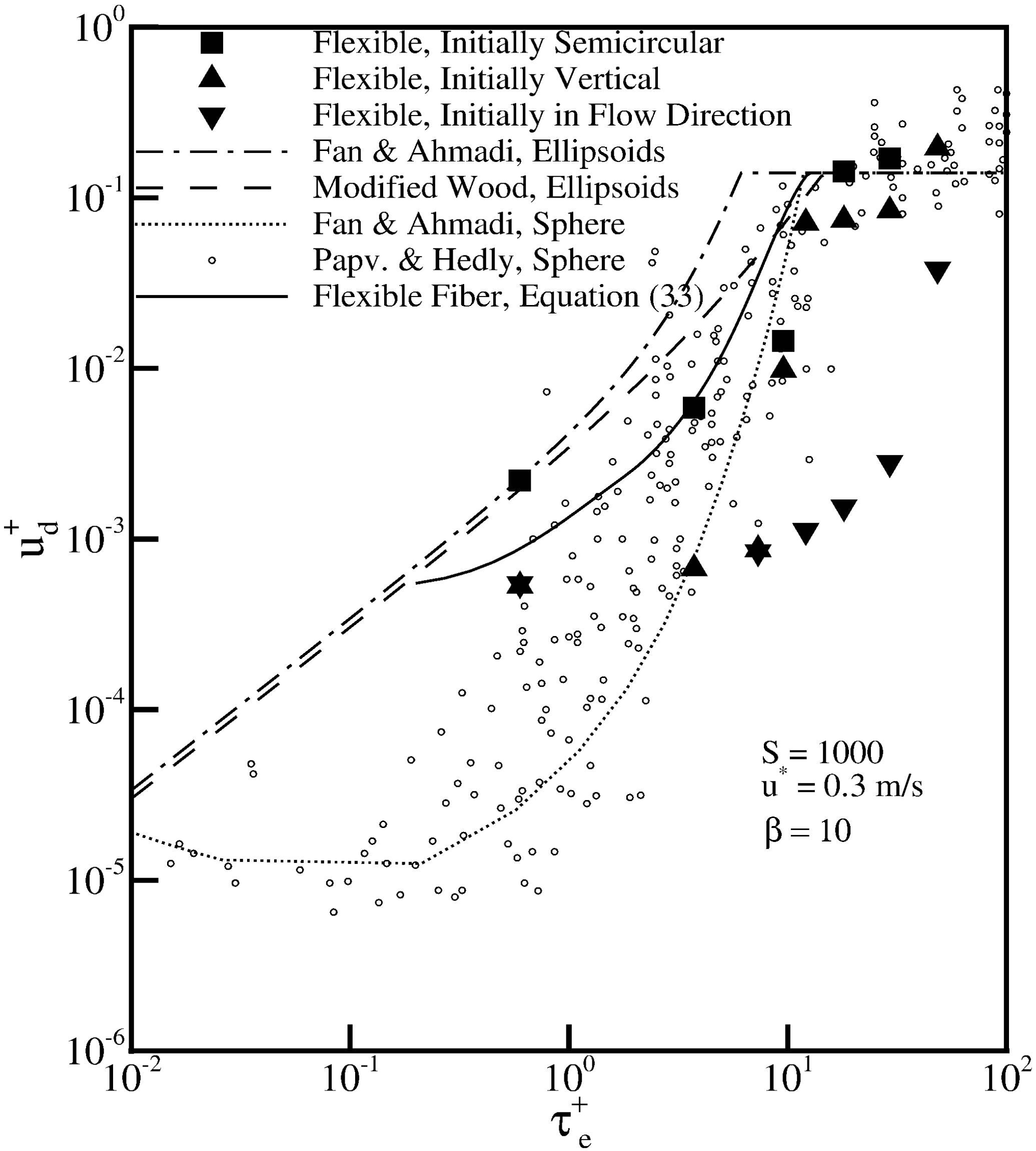
Sample Trajectories for Flexible String



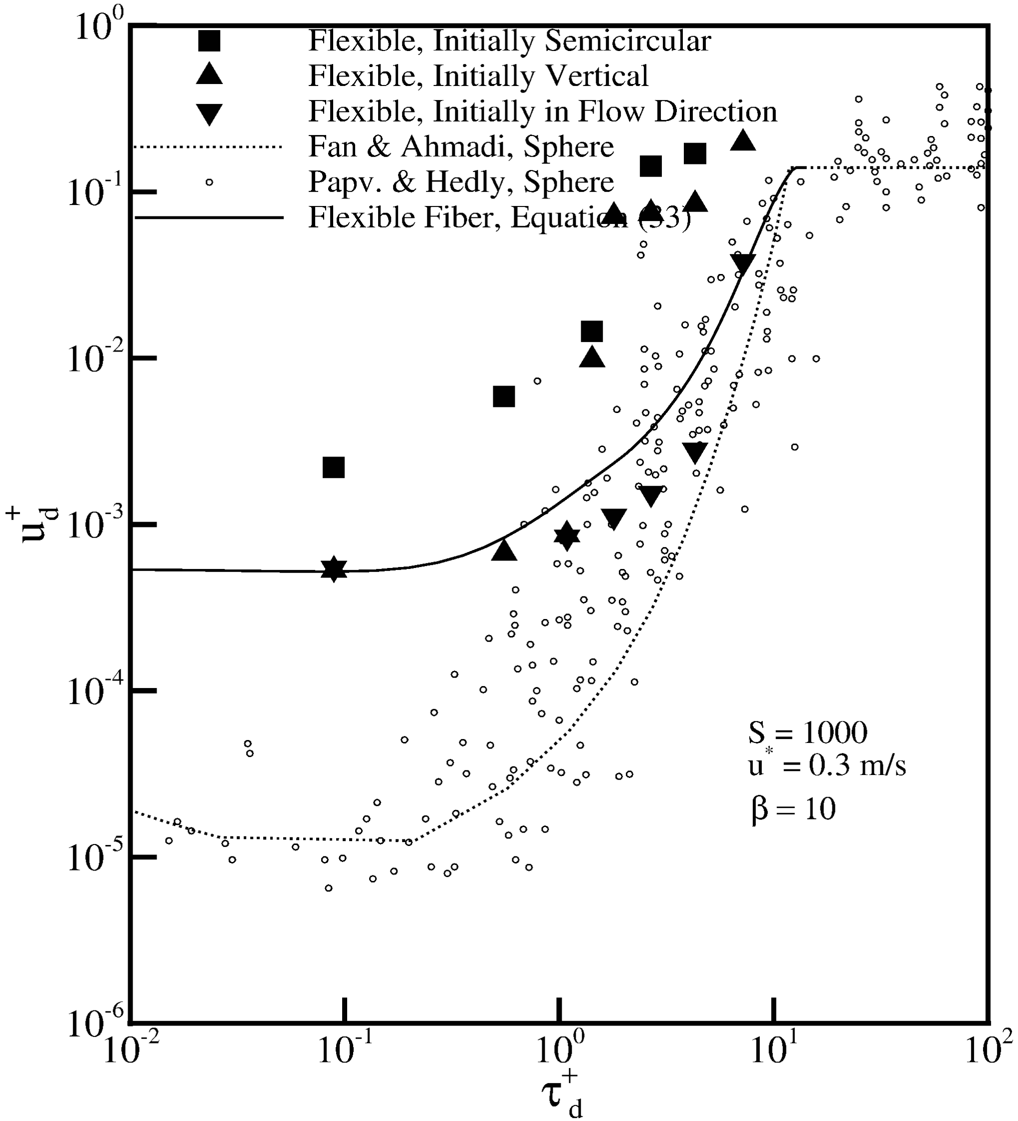
Sample Trajectories for Flexible String



Flexible String Deposition Rates



Flexible String Deposition Rates



Remarks-Sublayer

Clarkson University

- Semi-Empirical Models
- Free Flight Models
- Flow Structure Models
- Sublayer/Burst Models
- Deposition on Rough Walls
- Fiber Deposition
- Flexible Fiber Deposition

Turbulence

Clarkson University

- Direct Numerical Simulation
- Large Eddy Simulation
- Stress Transport Model
- Two-Equation Models

Governing Equations- RANS Models

Clarkson University

Reynolds

$$\left(\frac{\partial}{\partial t} + U_j \frac{\partial}{\partial x_j}\right)U_i = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x_j}\overline{u_i' u_j'}$$

Mass

$$\frac{\partial U_i}{\partial x_i} = 0$$

4 Equations for 11 Unknowns

$$U_i,\ \overline{u_i' u_j'},\ P,\ \varepsilon$$

Stress Transport Model

Clarkson University

Launder-Reece-Rodi

$$\underbrace{\left(\frac{\partial}{\partial t}+U_k\frac{\partial}{\partial x_k}\right)\overline{u_i'u_j'}}_{\text{Convection}} = \underbrace{-\left[\overline{u_j'u_k'}\frac{\partial U_i}{\partial x_k}+\overline{u_i'u_k'}\frac{\partial U_j}{\partial x_k}\right]}_{\text{Production}} - \underbrace{\frac{2}{3}\delta_{ij}\varepsilon}_{\text{Dissipation}}$$

$$\underbrace{-c_1\frac{\varepsilon}{k}\left(\overline{u_i'u_j'}-\frac{2}{3}\delta_{ij}k\right)+\left(\varphi_{ij}^{(2)}+\varphi_{ji}^{(2)}\right)}_{\text{Pressure-strain}}+\underbrace{\left(\varphi_{ij}^{(w)}+\varphi_{ji}^{(w)}\right)}_{\text{Wall effects}}$$

$$\underbrace{+c_s\frac{\partial}{\partial x_k}\left\{\frac{k}{\varepsilon}\left[\overline{u_i'u_l'}\frac{\partial\overline{u_j'u_k'}}{\partial x_l}+\overline{u_j'u_l'}\frac{\partial\overline{u_k'u_i'}}{\partial x_l}+\overline{u_k'u_l'}\frac{\partial\overline{u_i'u_j'}}{\partial x_l}\right]\right\}}_{\text{Diffusion}}$$

Stress Transport Model

Clarkson University

Dissipation

$$\underbrace{\left(\frac{\partial}{\partial t} + U_k \frac{\partial}{\partial x_k}\right)\varepsilon}_{\text{Convection}} = \underbrace{c_\varepsilon \frac{\partial}{\partial x_k}\left(\frac{k}{\varepsilon}\overline{u_k' u_i'}\frac{\partial \varepsilon}{\partial x_i}\right)}_{\text{Diffusion}}$$

$$\underbrace{-c_{\varepsilon 1}\frac{\varepsilon}{k}\overline{u_i' u_k'}\frac{\partial U_i}{\partial x_k}}_{\text{Generation}} - \underbrace{c_{\varepsilon 2}\frac{\varepsilon^2}{k}}_{\text{Destruction}}$$

Instantaneous Turbulent Fluctuation Velocity

Clarkson University

- Direct Numerical Simulation
- Subgrid Scale Simulation
- Gaussian Models
  - Filtered White Noise
  - Eddy Life Time
- Pdf – Based Model

Instantaneous Turbulent Fluctuation Velocity

Clarkson University

Instantaneous Velocity

Thompson (1987)

$$\frac{d\mathbf{u}_i}{dt} = \frac{\mathbf{u}_i - \bar{\mathbf{u}}_i}{T_L} + \sqrt{\frac{2\,\overline{\mathbf{u}_i'^{\,2}}}{T_L}}\,\zeta(t)$$

Lagrangian Time Macro-Scale

$$T_L = \int_0^\infty \frac{\overline{u'^p(t)\,u'^p(t+\tau)}}{\overline{u'^p u'^p}}\,d\tau$$

Instantaneous Turbulent Fluctuation Velocity

Clarkson University

Instantaneous Velocity

Iliopoulos et al. (2003) and Dehbi (2008) included the drift term

$$\frac{d\mathbf{u}_2}{dt} = \frac{\mathbf{u}_2 - \bar{\mathbf{u}}_2}{T_L} + \sqrt{\frac{2\,\overline{\mathbf{u}_2'^2}}{T_L}}\,\zeta(t) + \frac{1}{2(1+Stk)}\frac{\partial \overline{\mathbf{u}_2'^2}}{\partial x_2}$$

$$Stk = \frac{\tau_p}{T_L}$$

Pdf Model for Velocity-Velocity Gradient

Clarkson University

Joint Velocity, Velocity-Gradient pdf

$$\frac{\partial f}{\partial t} = -U_i \frac{\partial f}{\partial x_i} + \frac{\partial \langle p \rangle}{\partial x_i}\frac{\partial f}{\partial U_i} + L_{ij}\frac{\partial}{\partial U_i}\left[f\left(U_j - \langle U_j \rangle\right)\right] + \frac{1}{2} C_o \nu H_{jk} H_{jk} \frac{\partial^2 f}{\partial U_i \partial U_i}$$

$$- \frac{\partial}{\partial H_{ij}}\left[M_{ij} f\right] + \frac{1}{2}\frac{\partial^2}{\partial H_{kl}\partial H_{pq}}\left[D_{ijkl} D_{ijpq} f\right]$$

$$L_{ij} = G_{ij} - \frac{3}{4} C_o \left(\omega - \langle \omega \rangle\right) B_{ij}^{-1}$$

$$G_{ij} = \frac{\varepsilon}{k}\left(\alpha_1 \delta_{ij} + \alpha_2 b_{ij} + \alpha b_{ij}^2\right) + H_{ijkl}\frac{\partial \langle u_k \rangle}{\partial x_1}$$

$$H_{ij} = \beta_2 \delta_{ik}\delta_{j1} + \beta_3 \delta_{i1}\delta_{jk} + \gamma_5 b_{ik}\delta_{j1} + \gamma_6 b_{i1}\delta_{jk}$$

Instantaneous Turbulent Fluctuation Velocity

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Langevin's Equation for Velocity and Velocity Gradient

$$b_{ij} = \frac{\langle u_i u_j \rangle}{\langle u_k u_k \rangle} - \frac{1}{3}\delta_{ij}.$$

$$M_{ij} = \frac{h_{ij} - H_{ij}}{T_\eta}.$$

$$du_i = -\frac{\partial \langle p \rangle}{\partial x_i} dt + L_{ij} \cdot \left(u_j - \langle u_j \rangle\right) dt + \left(C_o \varepsilon\right)^{1/2} dW_i,$$

$$dh_{ij} = -M_{ij} dt + D_{ijkl} dW_{kl}$$

$$h_{ij} = \frac{\partial u_i}{\partial x_j}$$

Haworth and Pope (1986), Girimaji and Pope (1990), Kvasnak et al. (2004)

Particle Equation

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$$\frac{du_i^p}{dt} = \underbrace{\frac{C_D \, Re_P}{24} \frac{1}{\tau} \left(u_i - u_i^p\right)}_{\text{Drag force}} + \underbrace{f_i^L}_{\text{Lift force}}$$

$$+ \underbrace{g_i}_{\text{Gravitational force}} + \underbrace{f_i^E}_{\text{Electric force}} + \underbrace{n_i(t)}_{\text{Brownian force}}$$

Assumptions: Dilute Flows, One-Way Interaction, Neglect Particle Collisions

$$C_D = \frac{24[1 + 0.15\,Re^{0.687}]}{Re}$$

$$1 < Re < 1000$$

Brownian Motion

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Spectral Intensity

White Noise Model

$$S_{nn} = \frac{2kT}{\pi\tau}$$

Particle Relaxation Time

$$\tau = \frac{d^2 \rho^p C_c}{18\mu} = \frac{S d^2 C_c}{18\nu}$$

Sample Brownian Excitation

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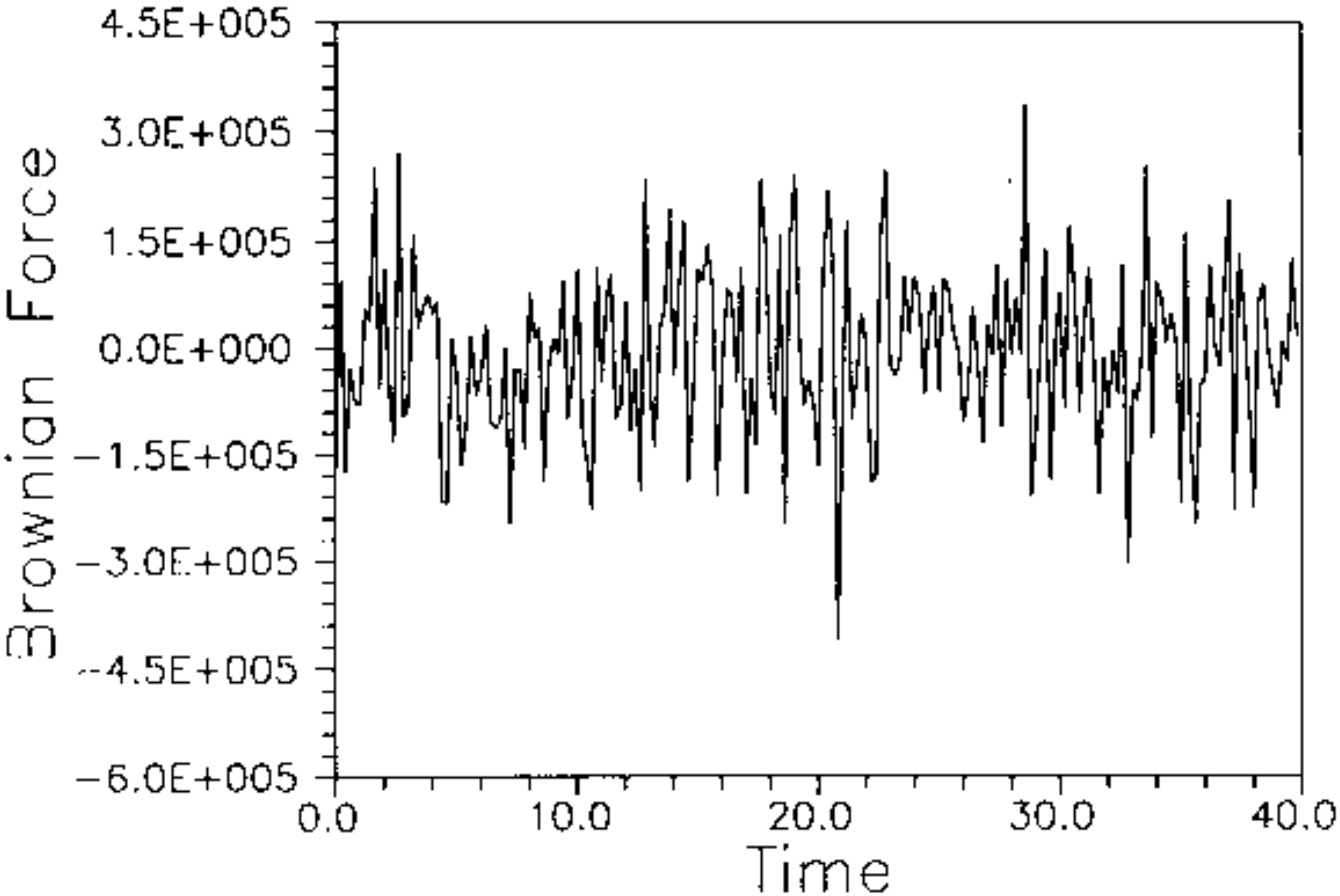

Ounis, Ahmadi and McLaughlin (1991)

Brownian Motion

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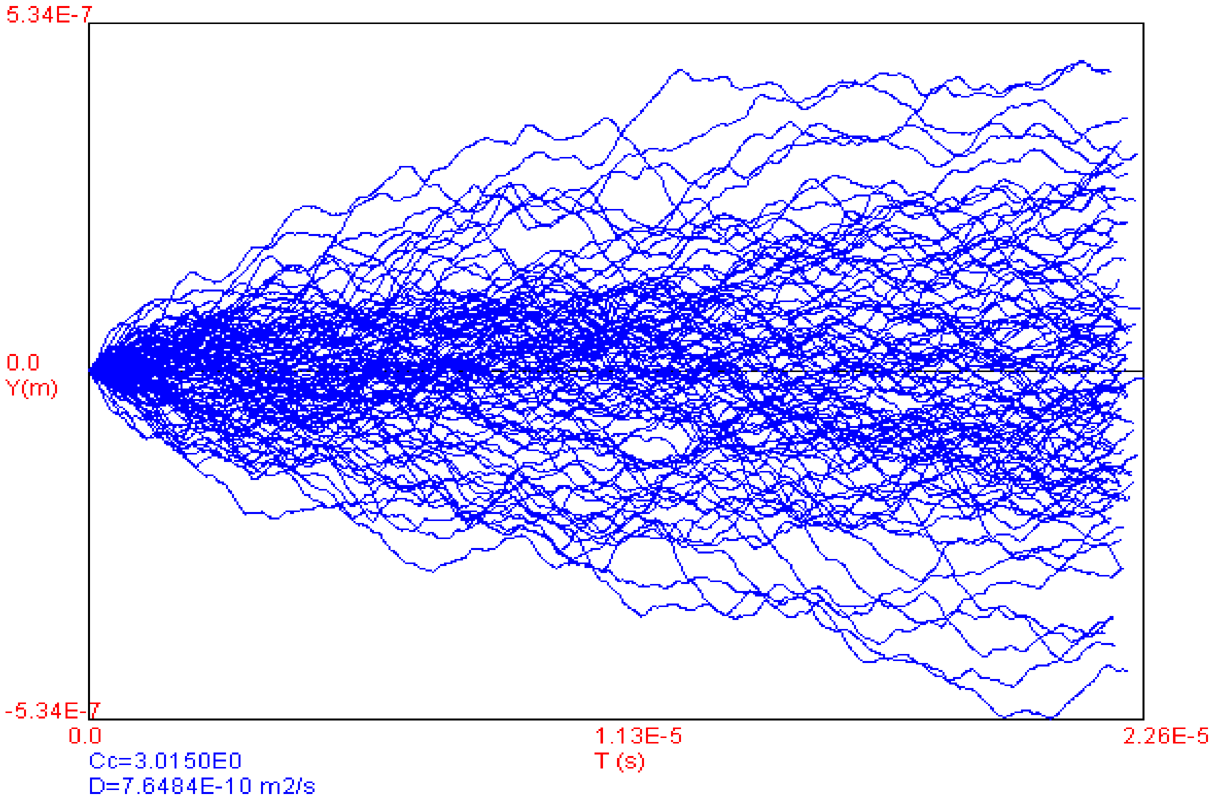
CRCD Web-Based Course Module



Particle diameter (m):	1e-7	Flow velocity Umax (m/s):	1
Particle density ratio to flow:	2000	Flow density (kg/m3):	1.12
Number of particles:	100	Flow viscosity (m2/s):	1.51e-5
Iterating steps:	1000	☑ Gravity	Plot y variance
☐ Set range of y (m): +/-		☑ Brownian force	Plot particle trajectories

Sample Brownian Dispersioin

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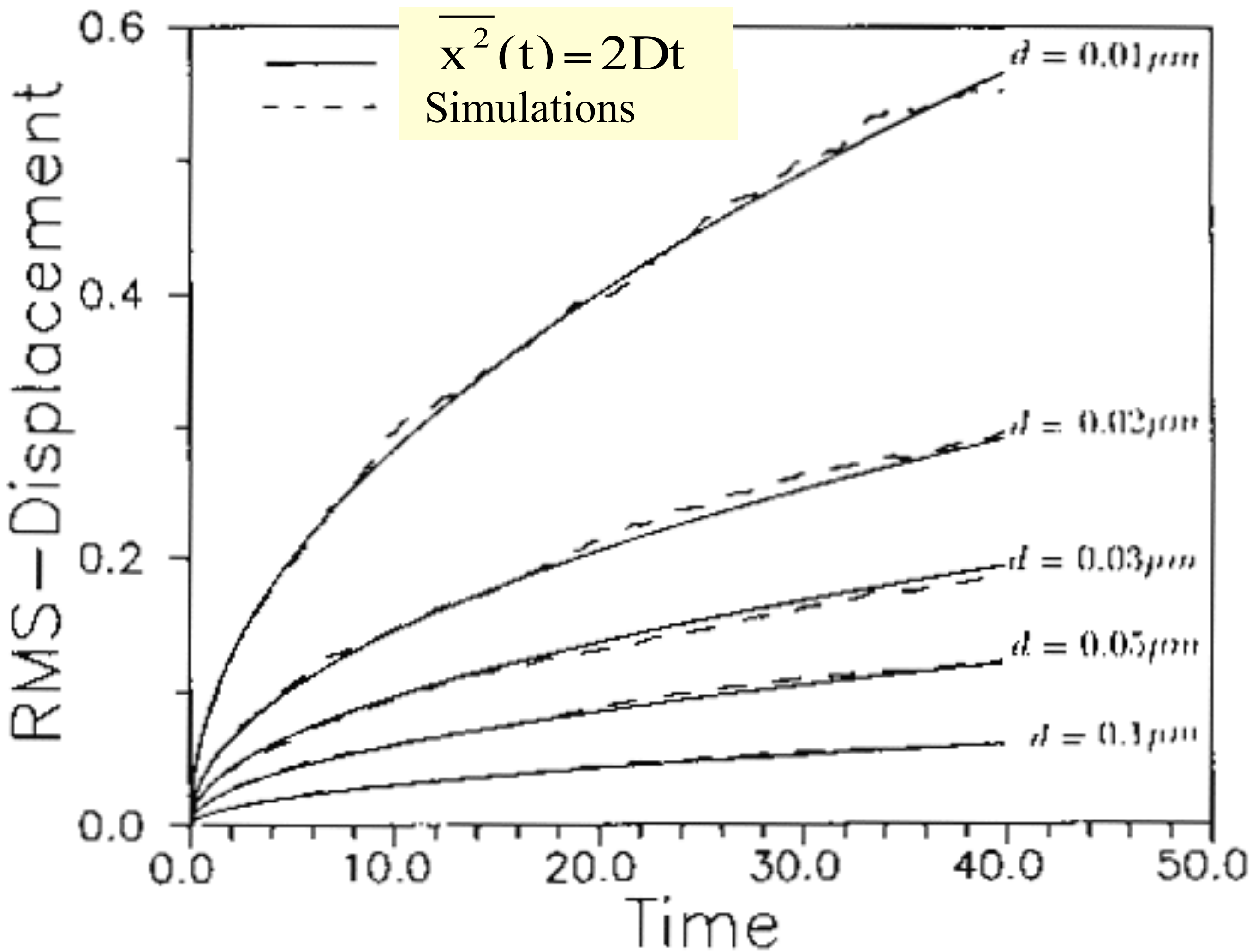

Particle Deposition in a Duct

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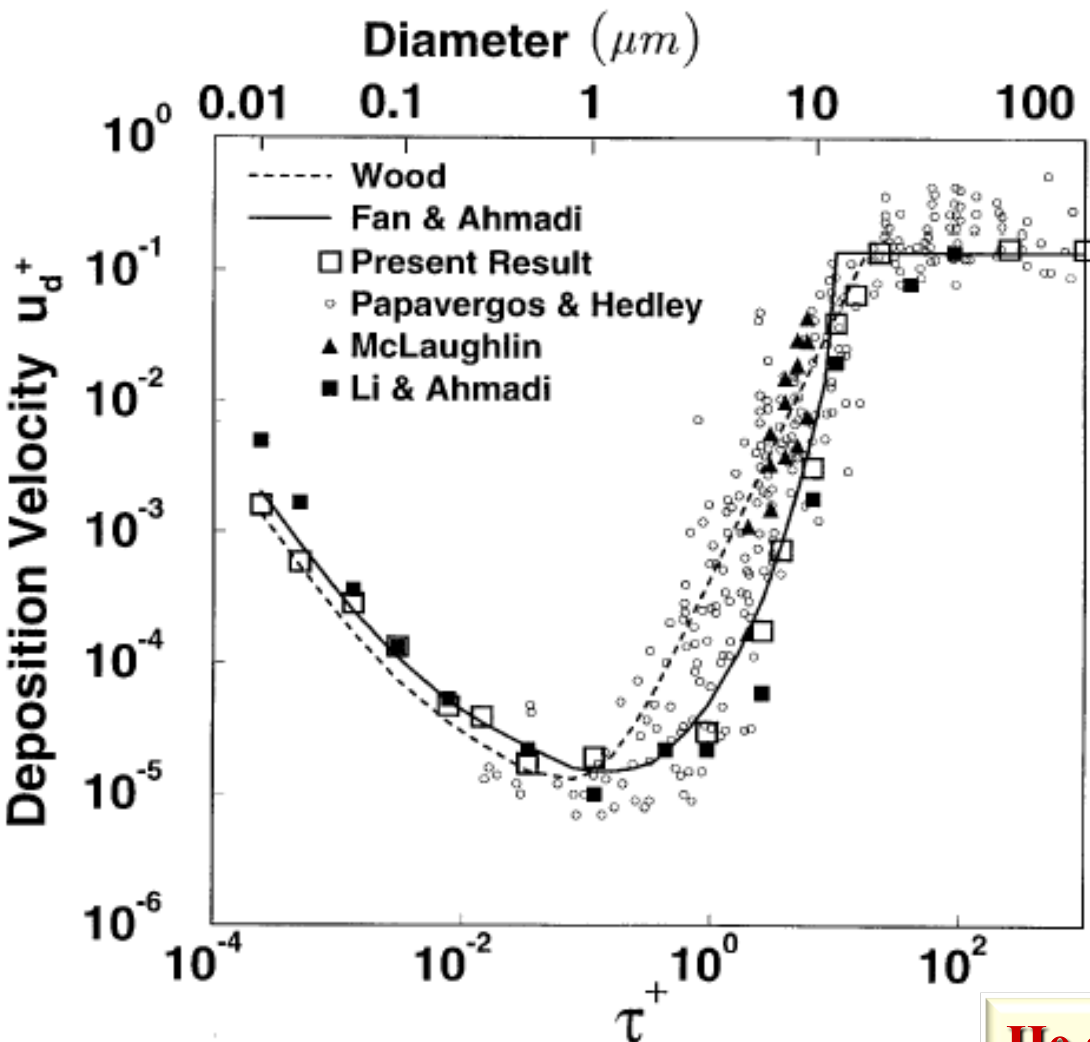

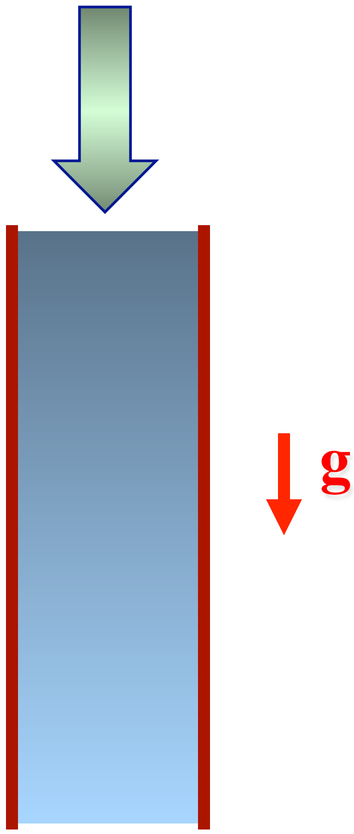

He and Ahmadi (1999)

Particle Deposition in a Duct

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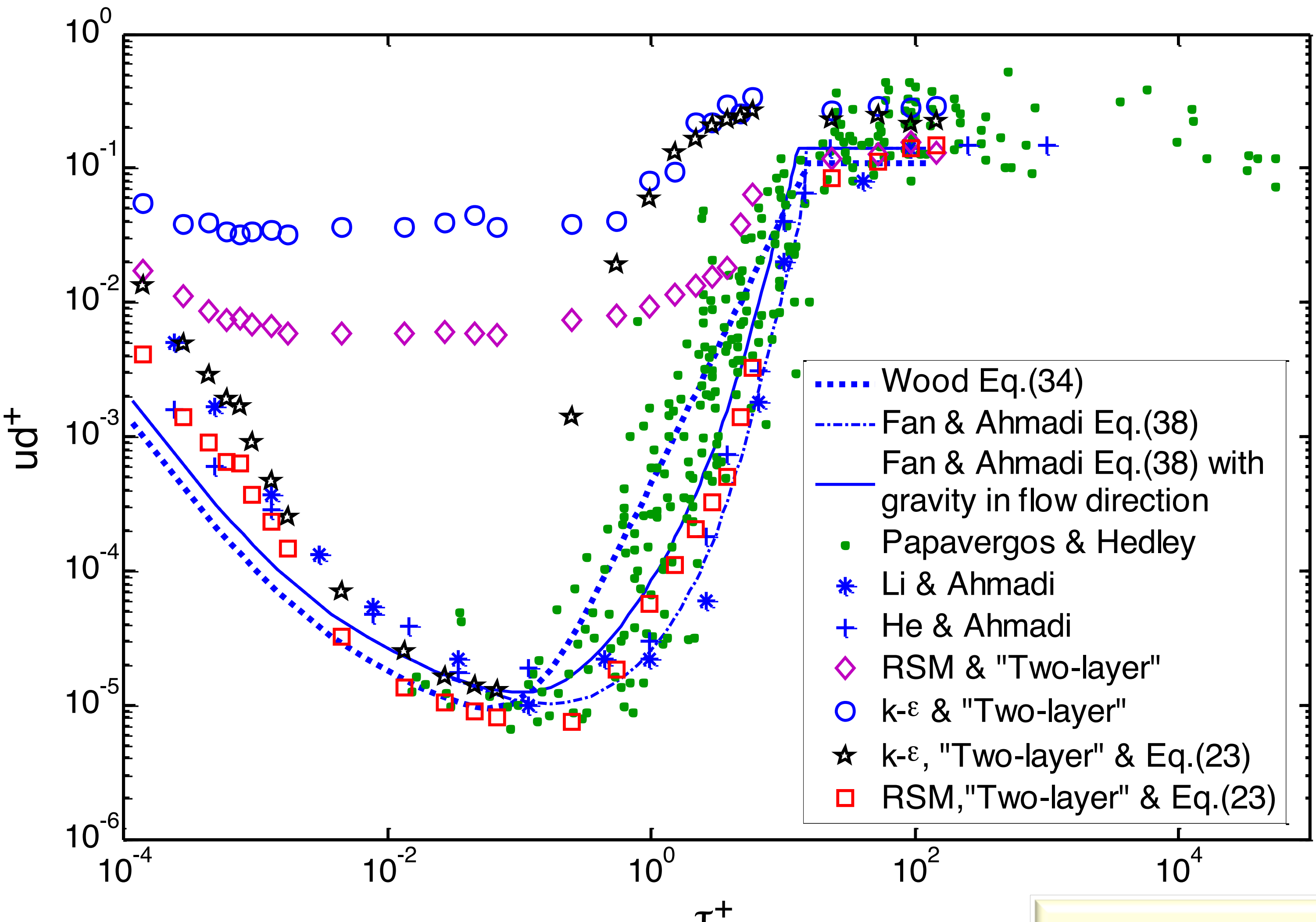

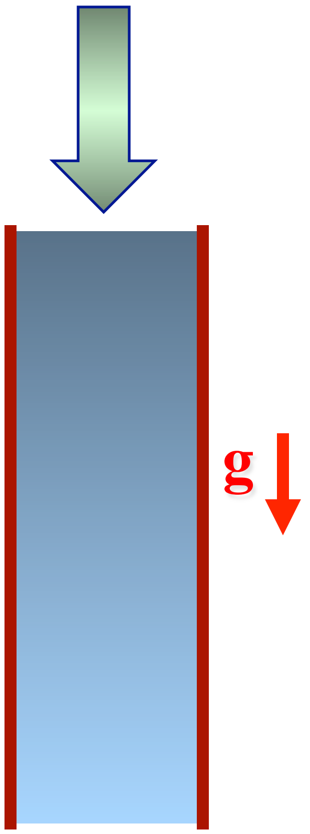

Tian and Ahmadi (2007)

Turbulence Near Wall Model

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Quadratic Variation Near Wall

Hinze, 1975

$$\sqrt{\overline{v'^2}} \propto y^2 \qquad y \to 0$$

$$v^+ = Ay^{+2} \qquad y^+ < 4$$

$$y^+ = \frac{yu^*}{\nu} \qquad v^+ = \frac{\sqrt{\overline{v'^2}}}{u^*} \qquad A = 0.008$$

Li and Ahmadi, 1993

Ounis, et al. 1993 (DNS)

Dehbi, 2001

Abouali et al., 2013

Turbulence Near Wall Model

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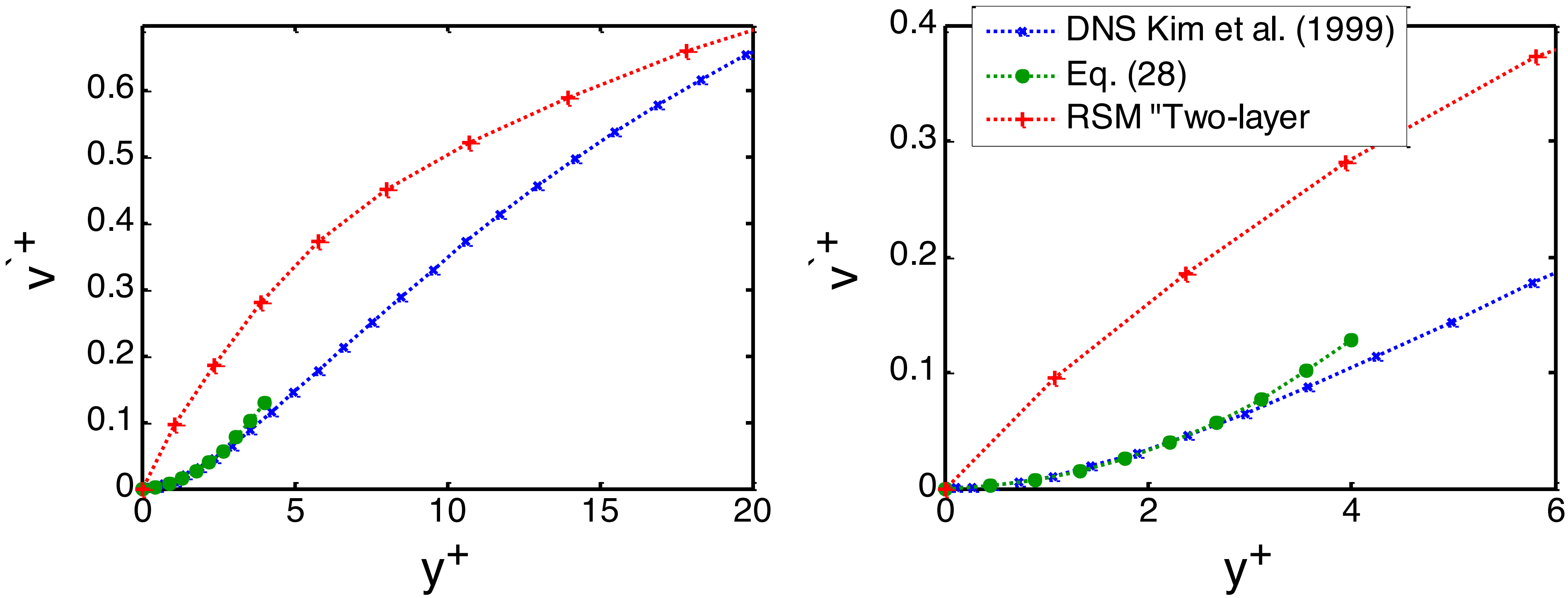
RSM with two-layer vs. near wall correction by Li & Ahmadi (1993)



Fiber Transport and Deposition

Equivalent Spheres Diameter

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Equivalent Volume

$$d_{ev} = 2a\beta^{\frac{1}{3}}$$

Equivalent Stokes diameter Shapiro and Goldenburg (1993)

$$d_{Stokes\_Shapiro} = 2a\sqrt{\frac{\beta\ln(\beta+\sqrt{\beta^2-1})}{\sqrt{\beta^2-1}}}$$

Equivalent Stokes diameter Fan and Ahmadi (1995)

$$d_{Stokes\_Fan} = 6a\sqrt{\frac{2\beta}{k_{xx}+k_{yy}+k_{zz}}}$$

Equivalent Aerodynamic diameter, Stober (1972)

$$d_{Aerodynamic\_Stober} = d_{ve}\sqrt{\frac{\rho}{\rho_0\kappa}},$$

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

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

$$\kappa_{\perp} = \frac{\frac{8}{3}(\beta^2-1)\beta^{-\frac{1}{3}}}{\frac{2\beta^2-3}{\sqrt{\beta^2-1}}\ln(\beta+\sqrt{\beta^2-1})+\beta},\quad \kappa_{\parallel} = \frac{\frac{4}{3}(\beta^2-1)\beta^{-\frac{1}{3}}}{\frac{2\beta^2-1}{\sqrt{\beta^2-1}}\ln(\beta+\sqrt{\beta^2-1})-\beta},$$

$$\kappa_r = \frac{3\kappa_{\perp}\kappa_{\parallel}}{\kappa_{\perp}+2\kappa_{\parallel}}$$

Deposition Efficiency- Horizontal Duct Flows

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Chen and Yu (1991)

$$\eta = \alpha(\beta)\varepsilon$$

Laminar Flow

$$\alpha(\beta) = 1.698(0.28\frac{1}{\kappa_{\parallel}} + 0.73\frac{1}{\kappa_{\perp}} - 0.01) \qquad \varepsilon = \frac{\rho d_{ev}^2 gL}{48U_0 \mu R}$$

Asgharian and Anijilvel (1991)

$$\eta = f(\theta,\beta)\tau$$

$$f(\theta,\beta) = \beta^{-0.774}(-0.844\theta^0 + 14.4\theta^1 - 22.409\theta^2 + 16.586\theta^3 - 5.669\theta^4 + 0.726\theta^5)$$

$$\tau = \frac{\rho g b^2 \beta C}{18\mu U_0}$$

Current Study

$$\eta = \frac{1}{2u^*}\sqrt{\frac{Lg\nu\tau_{eq}^+}{2RU_0}}$$

Fully developed flow

$$\eta = \left(\frac{1}{2u^*}\sqrt{\frac{Lg\nu\tau_{eq}^+}{2RU_0}}\right)^{1.5} - \left(\frac{145}{\text{Re}}\right)^2 e^{-\tau^+} + \left(\frac{144.65}{\text{Re}}\right)^2$$

Developing flow

Sample Fiber Trajectory

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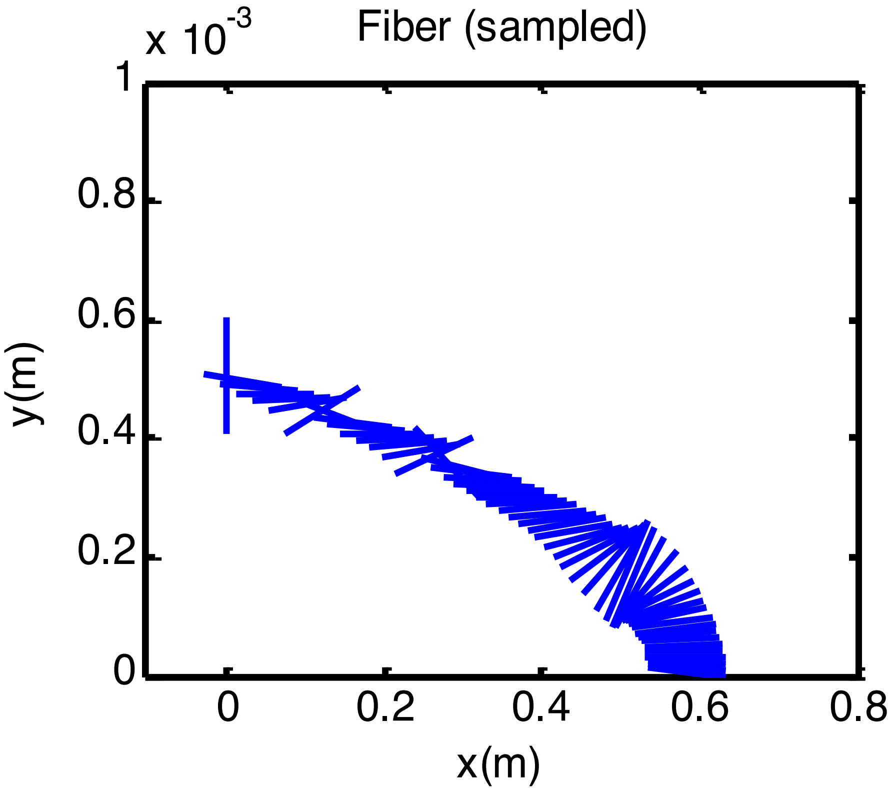
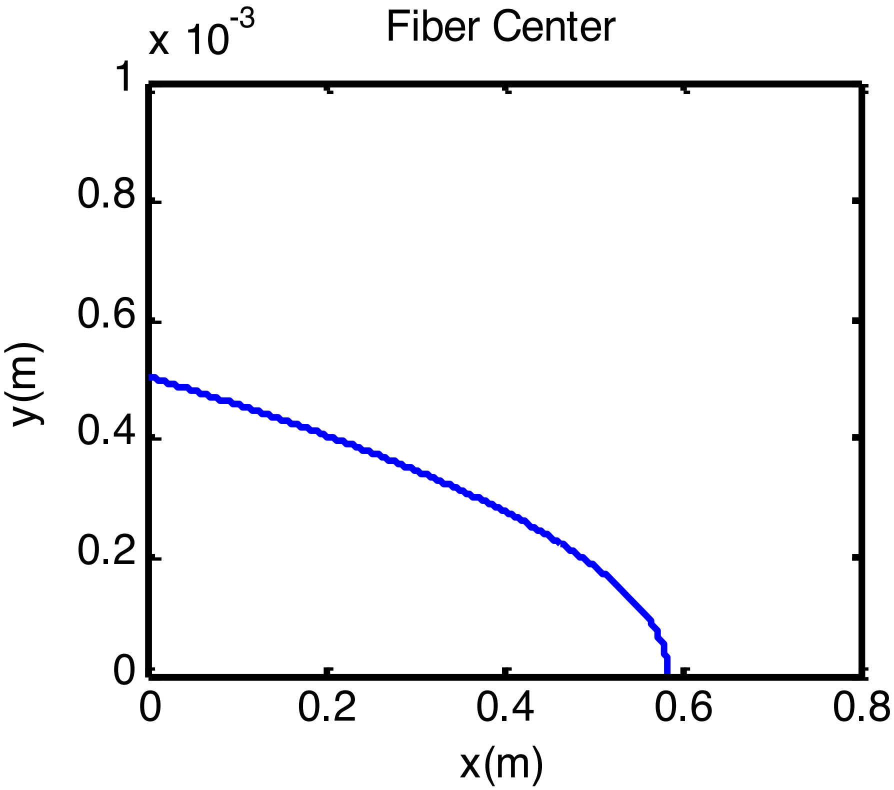
Laminar Flow





Horizontal Laminar Pipe Flow

Ellipsoidal Fiber Sedimentation Velocities

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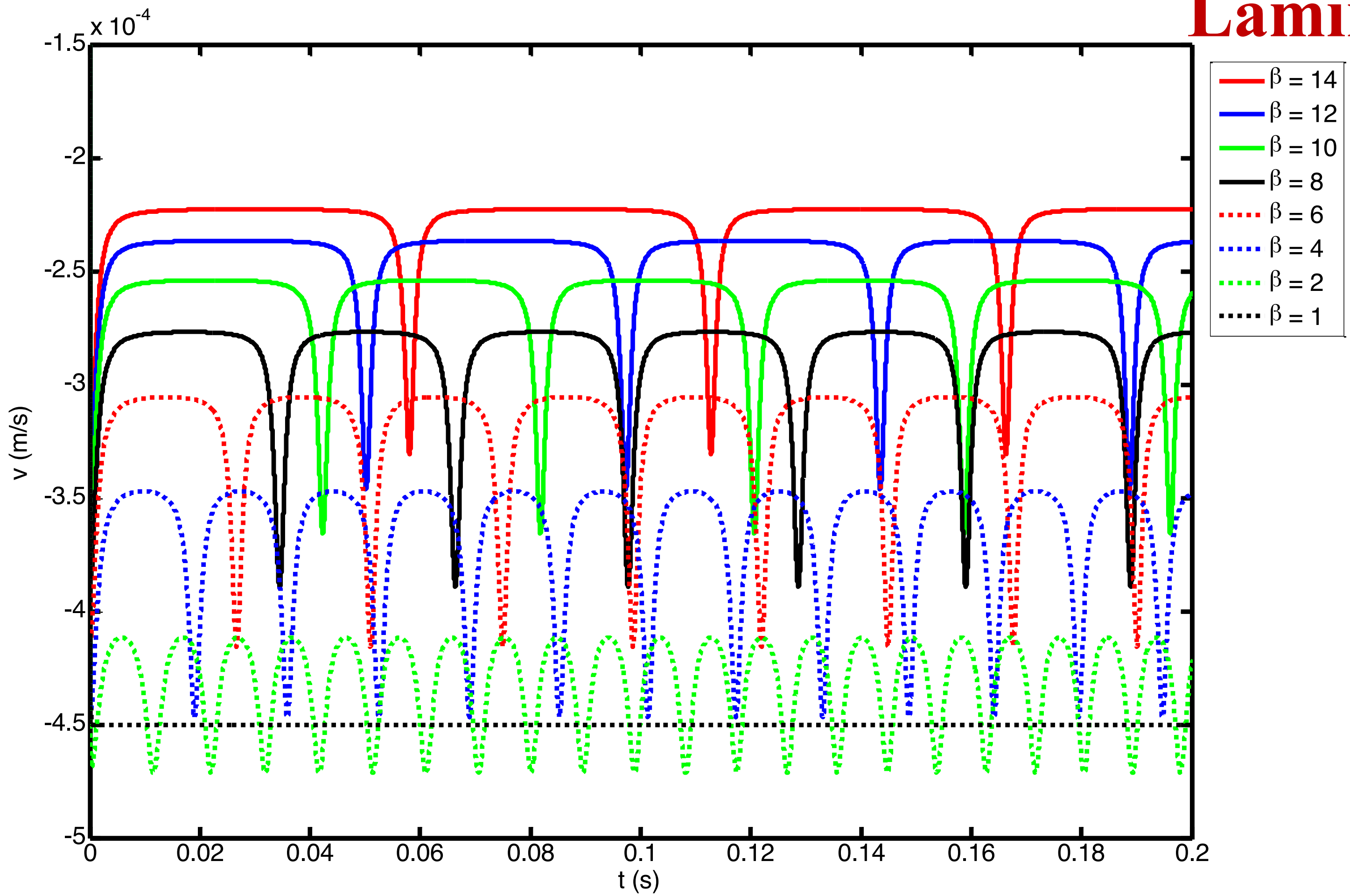
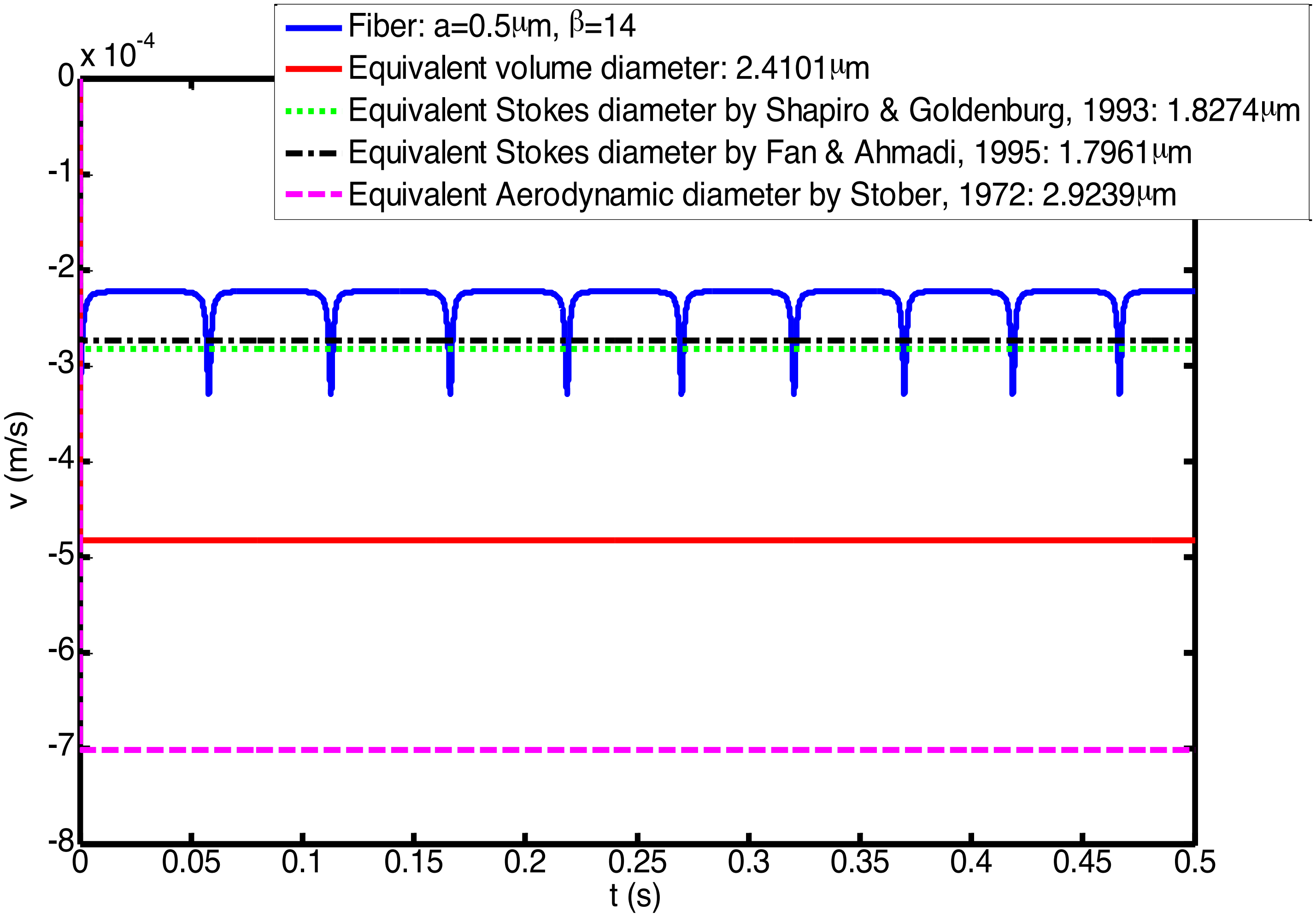
Laminar Flow



Fiber radius =0.5µm, aspect ratio from 1 to 14

Ellipsoidal Fiber Sedimentation Velocities

Clarkson University



Comparison of sedimentation terminal velocities of fibers and equivalent spheres.

Fiber Deposition Rate

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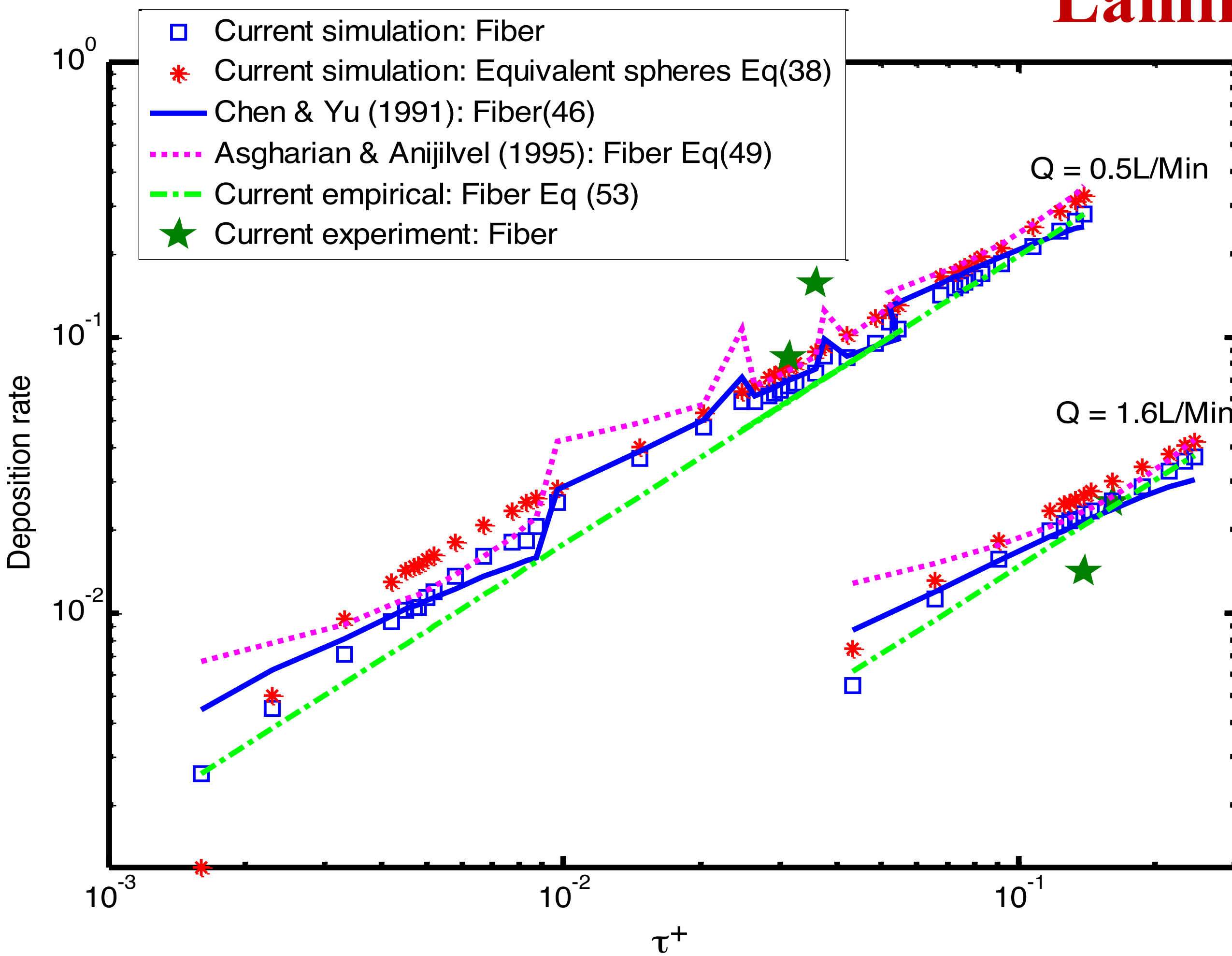
Laminar Flow



Deposition rates of glass fibers and the equivalent spheres.

Fiber Deposition Rate

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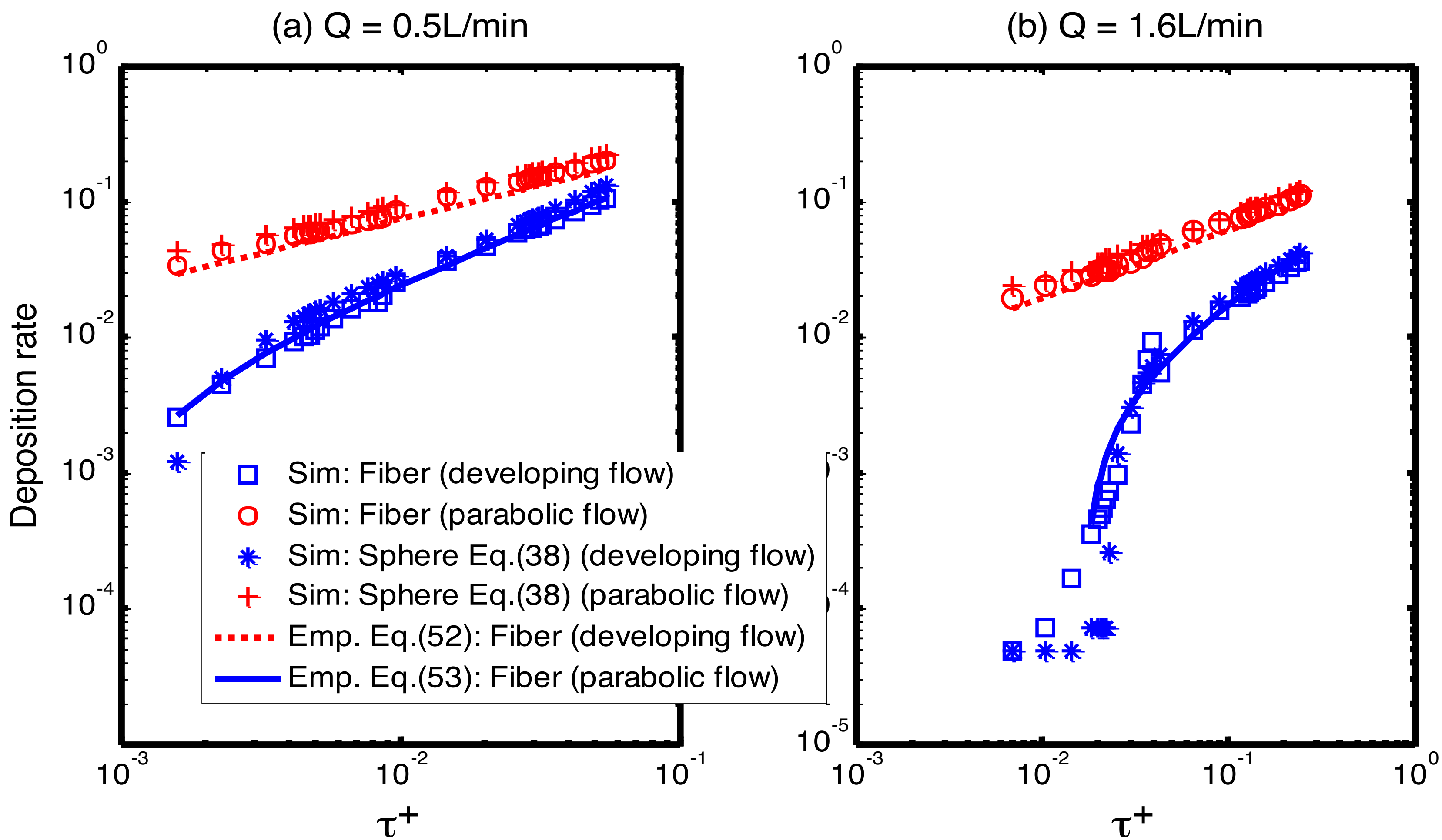
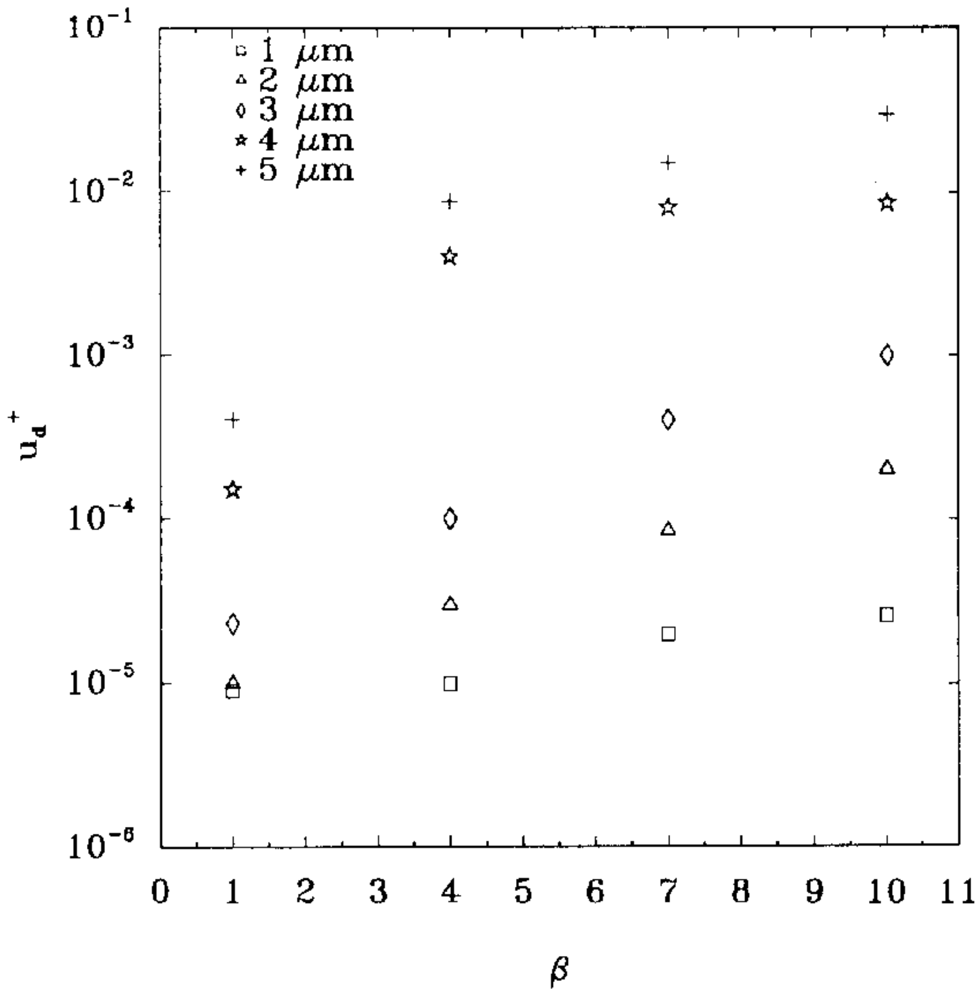
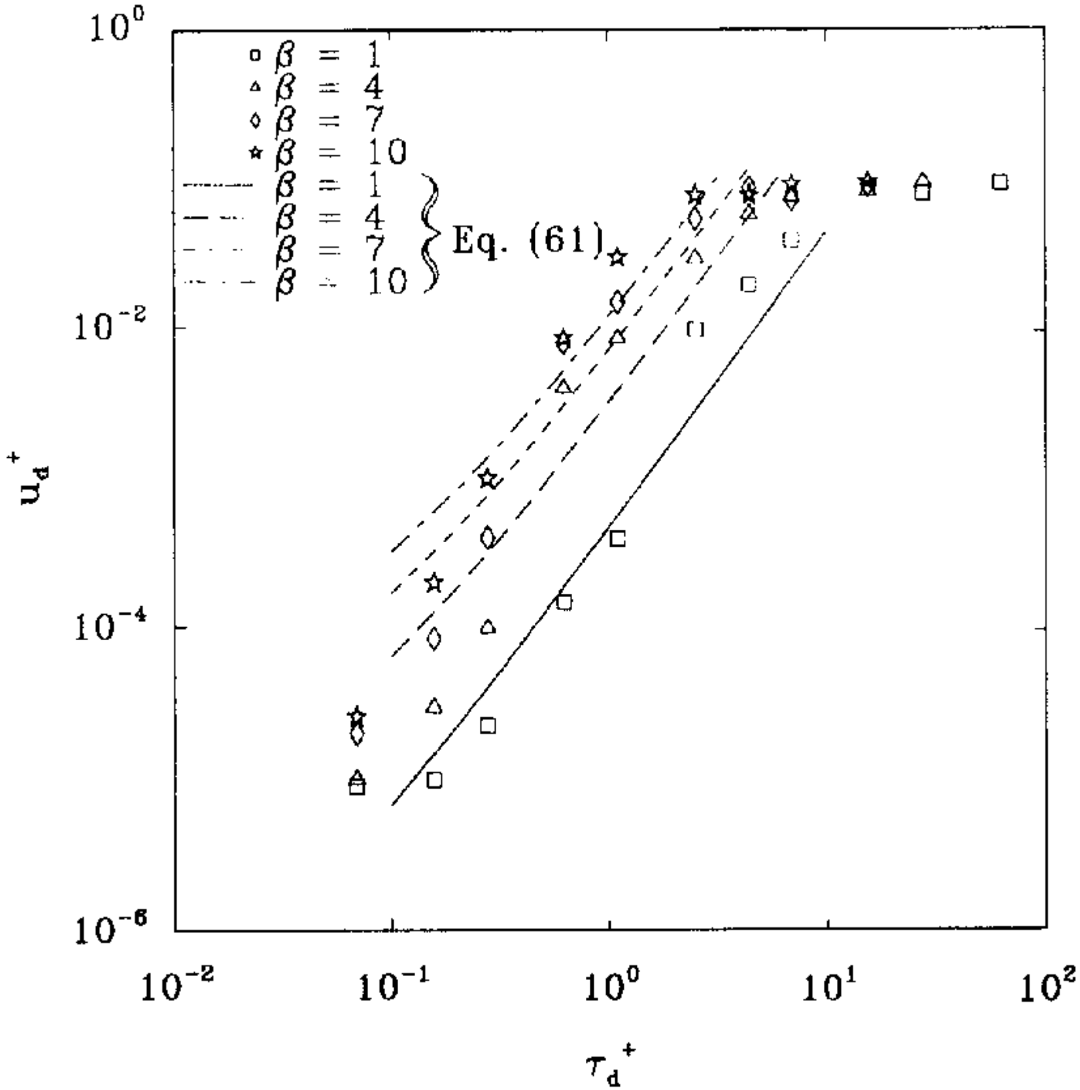


Comparison of deposition rates of the glass fibers in the horizontal pipe in developing flow and in parabolic flow

Deposition in Turbulent Flows



Fiber Deposition Velocity



Fiber Transport and Deposition

Fiber relaxation Time

$$\tau_{\text{vol}}^{+} = \frac{Sd^{+2}\beta^{2/3}}{18} = \tau_d^{+}\beta^{2/3}$$

$$\tau_{\text{eq}}^{+} = \frac{m_p u^{*2}}{\mu\nu}\frac{1}{\bar{K}} = \frac{Sd^{+2}}{18}\frac{\beta \ln(\beta + \sqrt{\beta^2 - 1})}{\sqrt{\beta^2 - 1}}$$

$$= \tau_d^{+}\frac{\beta \ln(\beta + \sqrt{\beta^2 - 1})}{\sqrt{\beta^2 - 1}}$$

$$\bar{K} = 3(K_{xx}^{-1} + K_{yy}^{-1} + K_{zz}^{-1})^{-1}$$

Fiber Transport and Deposition

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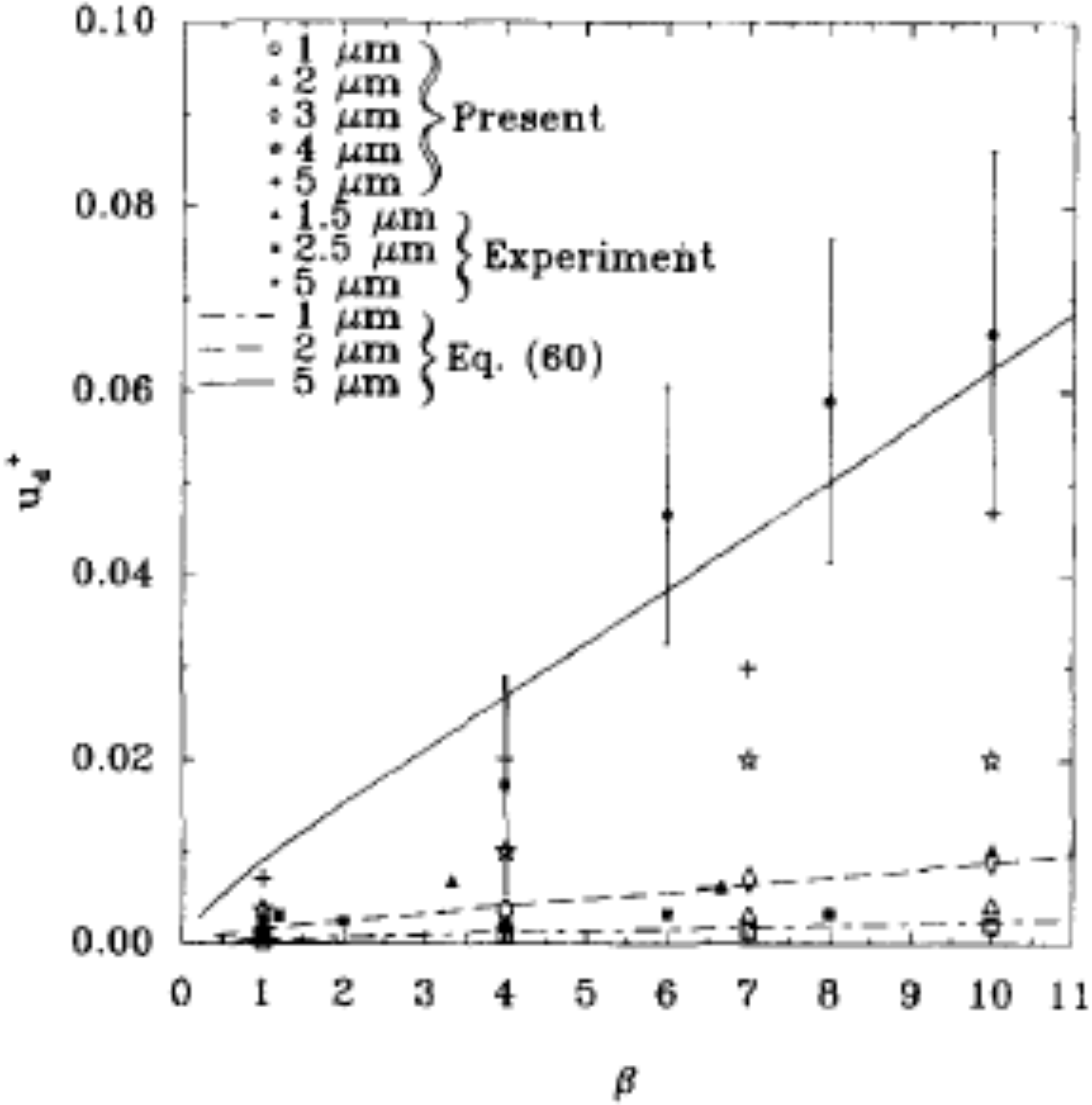

Fiber Transport and Deposition

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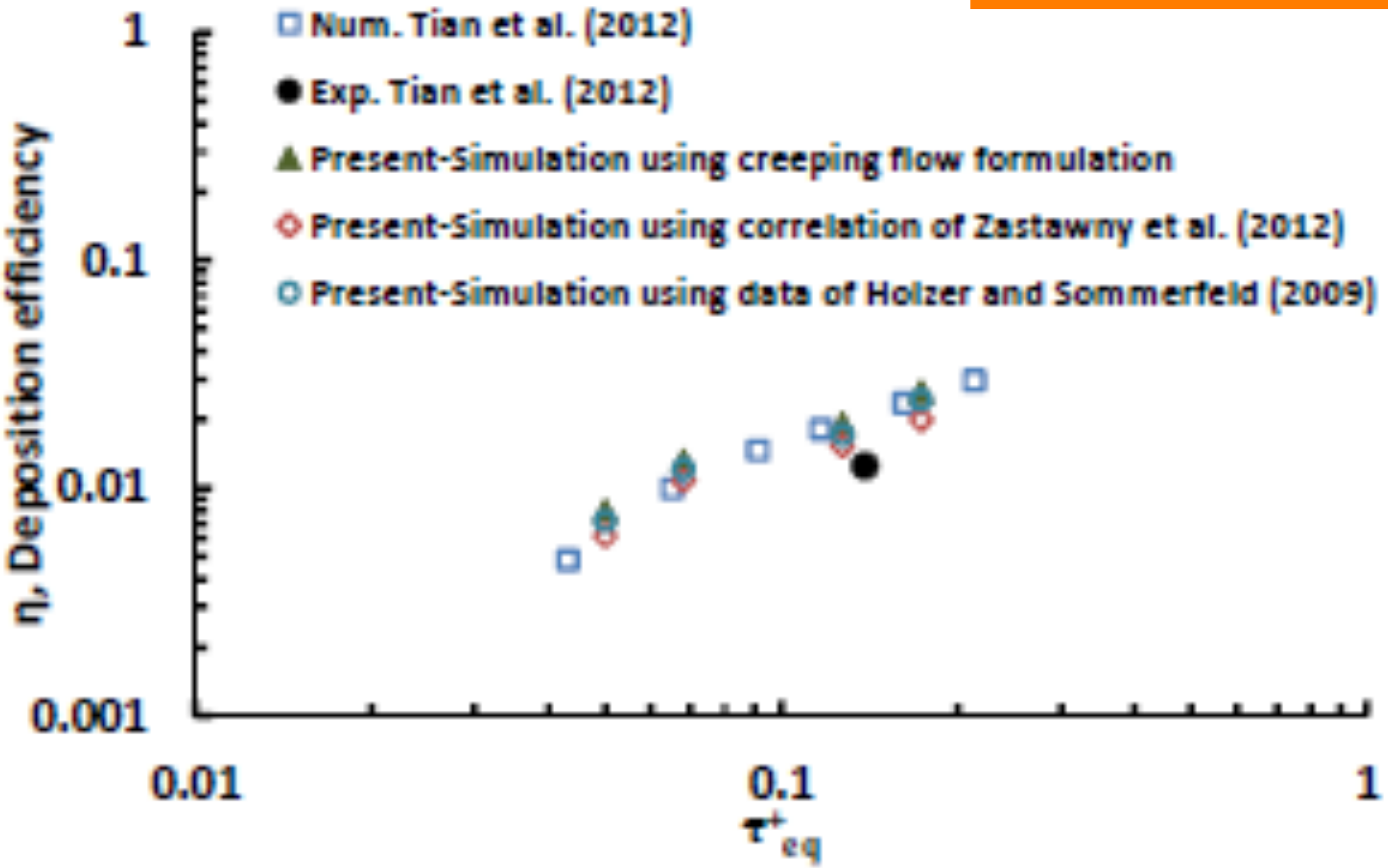
Creeping and Non-creeping Models

Laminar Pipe Flow, Q=1.6 L/min, D=4.2mm, L=70cm



Fiber Transport and Deposition

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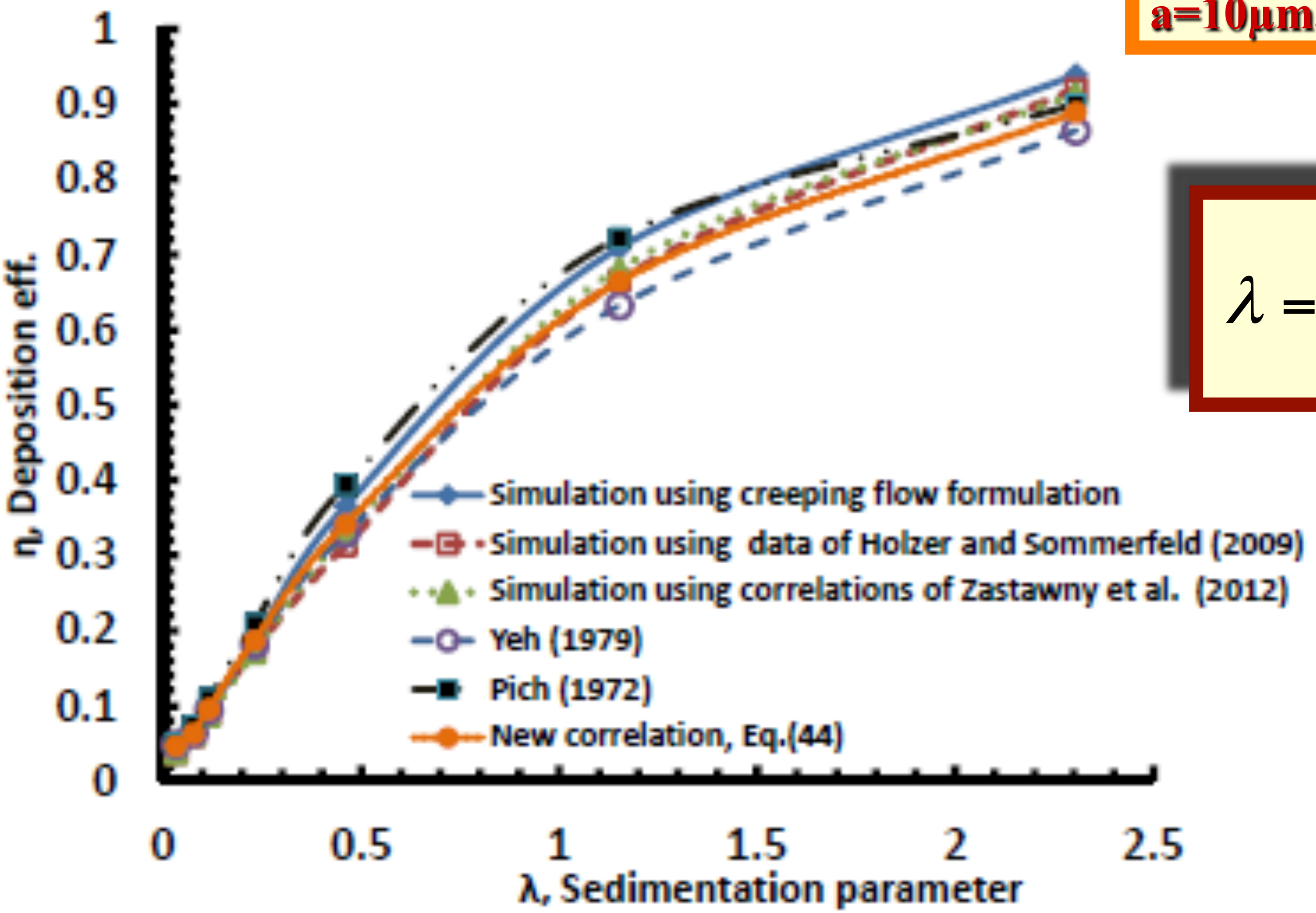
Creeping and Non-creeping Models

Laminar Pipe Flow, a=10μm, β=2

$$\lambda = \frac{\rho_p g \beta d^2}{18 \mu U}$$



Fiber Transport and Deposition

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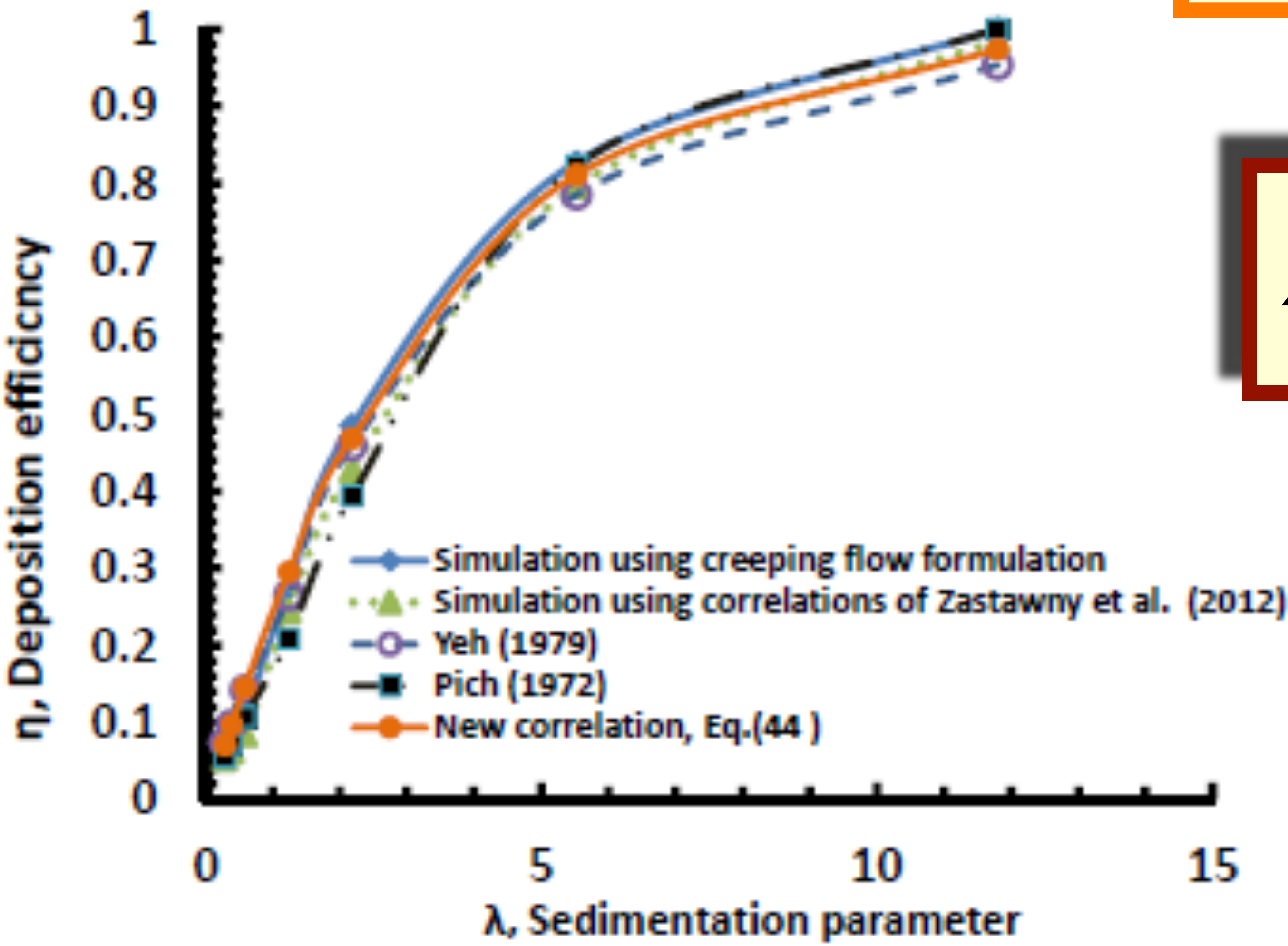
Creeping and Non-creeping Models

Laminar Pipe Flow, a=10μm, β=5



$$\lambda = \frac{\rho_p g \beta d^2}{18 \mu U}$$

Concluding Remarks

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- Using RANS for simulation of particle and fiber transport needs cares.
- RANS could be used for providing useful information for practical applications.
- Computational modeling could helps in optimizing industrial processes

Collaborators

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- Dr. P. Zamankhan
- Dr. L. Tian
- Dr. Kevin Shanley
- Dr. Mazyar Salmanzadeh
- Dr. F-G Fan
- Dr. C. He
- Dr. K. Nazridoust
- Dr. M. Soltani
- Dr. A. Mazaheri
- Dr. H. Zhang
- Dr. H. Nasr
- Prof. J. Tu
- Dr. Kiato
- Prof. Bohl
- Dr. M. Shams
- Prof. McLaughlin
- Prof. Saidi
- Dr. A. Li
- Dr. O. Abouali
- Dr. W. Kvasnak
- Dr. X. Zhang
- Dr. Tavakol

Thank You!

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Questions?