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Applications of Particle Transport, Deposition and Removal in Environmental and Biological Flows

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Outline

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- Aerosol Transport and Deposition
- Computational Modeling
- Particle Removal
- Environmental Applications
- Biomedical Applications
- Conclusions

Turbulence Modeling

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

Instantaneous Turbulent Fluctuation Velocity

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

Instantaneous Turbulent Fluctuation Velocity

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Instantaneous Velocity **Thompson (1987)**

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

Lagrangian Time Macro-Scale

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

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

$$C_D = \frac{24[1 + 0.15\,Re^{0.687}]}{Re} \qquad 1 < Re < 1000$$

Brownian Motion

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Spectral Intensity **White Noise Model**

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

Particle Relaxation Time

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

Sample Brownian Excitation

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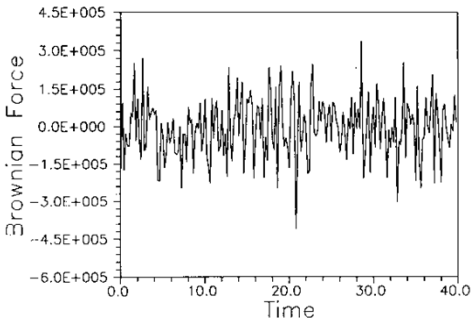

Ounis, Ahmadi and McLaughlin (1991)

Brownian Motion

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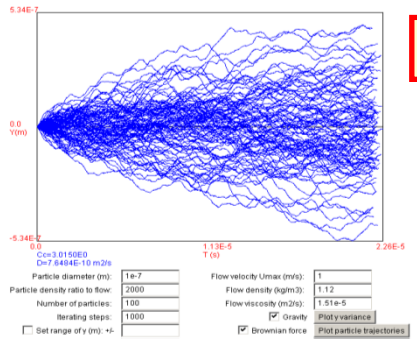

CRCD Web-Based Course Module

Sample Brownian Dispersioin

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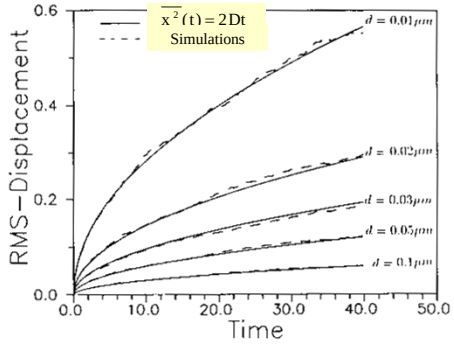

Particle Deposition in a Duct

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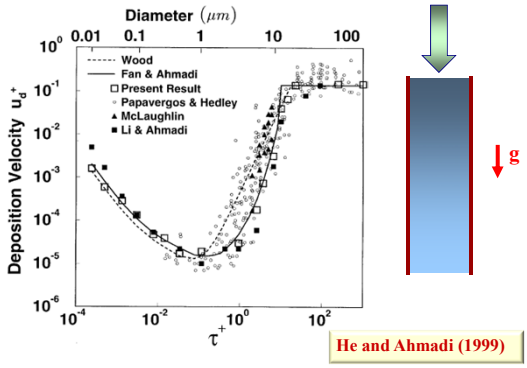

He and Ahmadi (1999)

Particle Deposition in a Duct

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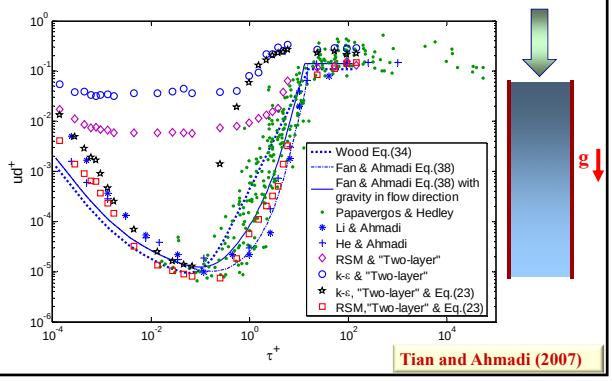

Tian and Ahmadi (2007)

Turbulence Near Wall Model

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Quadratic Variation Near Wall

Hinze, 1975 $\sqrt{\overline{v'^2}} \propto y^2$ $\quad y \to 0$

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

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

Li and Ahmadi, 1993

Ounis, et al. 1993 (DNS)

Respiratory Deposition

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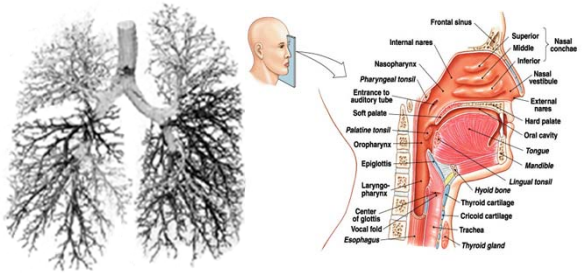
Particle and fiber deposition in human lung and nose

EPA

NIOSH



Multi-Level Lung Model

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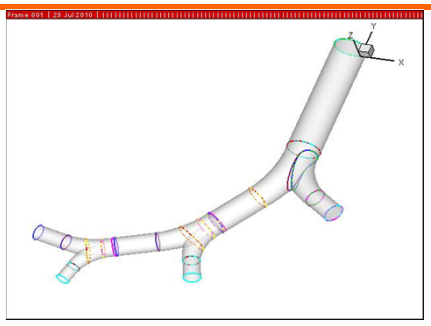

Multi-Level Bifurcation Model

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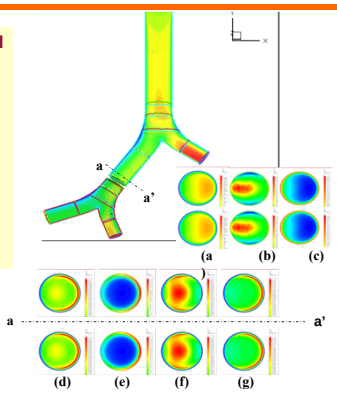
The schematics of multi-level bifurcation model

At interface aa':

- **(a) velocity magnitude**
- **(b) x- velocity**
- **(c) y- velocity**
- **(d) turbulence kinetic energy**
- **(e) turbulence dissipation rate**
- **(f) Reynolds stress uu**
- **(g) Reynolds stress vv**



Lung Deposition

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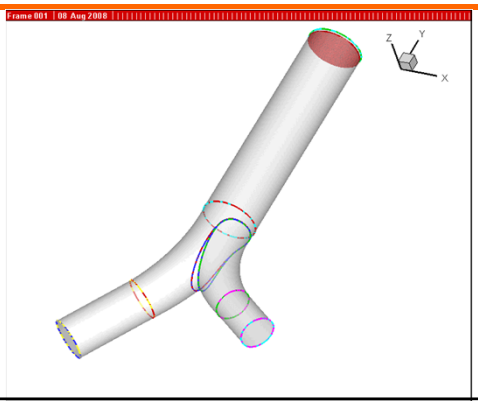

1 μm

Fiber Transport Model

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Translational Motion

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

Rotational Motion

$$I_{\hat{x}} \frac{d\omega_{\hat{x}}}{dt} - \omega_{\hat{y}}\omega_{\hat{z}}(I_{\hat{y}} - I_{\hat{z}}) = T_{\hat{x}}^h + T_{\hat{x}}^B(t),$$

$$I_{\hat{y}} \frac{d\omega_{\hat{y}}}{dt} - \omega_{\hat{z}}\omega_{\hat{x}}(I_{\hat{z}} - I_{\hat{x}}) = T_{\hat{y}}^h + T_{\hat{y}}^B(t),$$

$$I_{\hat{z}} \frac{d\omega_{\hat{z}}}{dt} - \omega_{\hat{x}}\omega_{\hat{y}}(I_{\hat{x}} - I_{\hat{y}}) = T_{\hat{z}}^h + T_{\hat{z}}^B(t),$$

Fiber Transport Model

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Translational Brownian Force

$$<\hat{\mathbf{f}}^B(t)>=0, \quad <\hat{\mathbf{f}}^B(t)\otimes\hat{\mathbf{f}}^B(t+t')>=\pi S^t\delta(t')$$

$$S_{\hat{i}\hat{i}}^t = 2KTR_{\hat{i}\hat{i}}^t/\pi$$

Rotational Brownian Torque

$$<\hat{\mathbf{T}}^B(t)>=0, \quad <\hat{\mathbf{T}}^B(t)\otimes\hat{\mathbf{T}}^B(t+t')>=\pi S^r\delta(t')$$

$$S_{\hat{i}\hat{i}}^r = 2KTR_{\hat{i}\hat{i}}^r/\pi$$

Fiber Transport and Deposition

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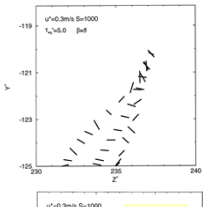
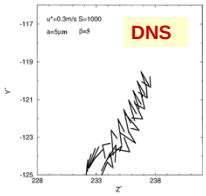
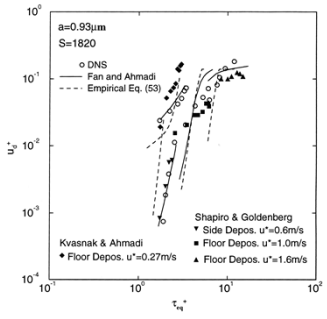


DNS





Ellipsoidal Fibers
Duct Flows

Fiber Transport and Deposition

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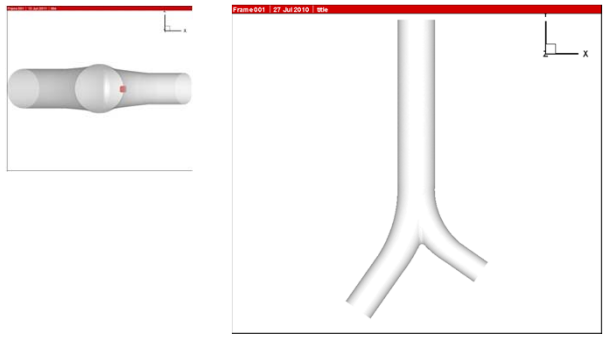

d = 0.1 µm, aspect ratio = 12, length = 1.2 µm

Fiber Deposition

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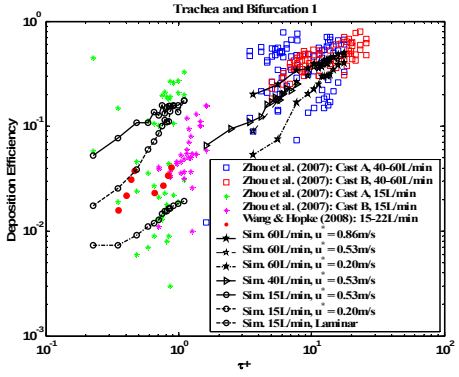

Airflow in the Nasal Cavity

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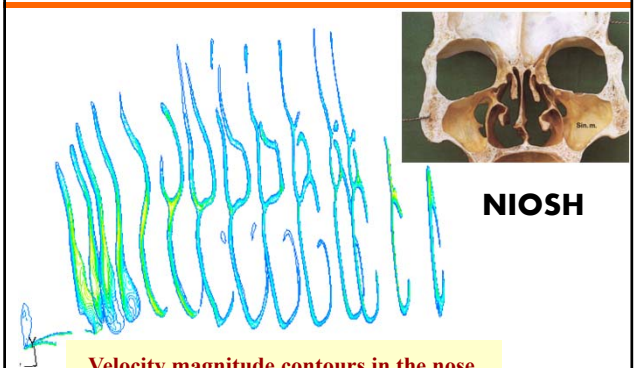

NIOSH

Velocity magnitude contours in the nose.

Nasal Deposition

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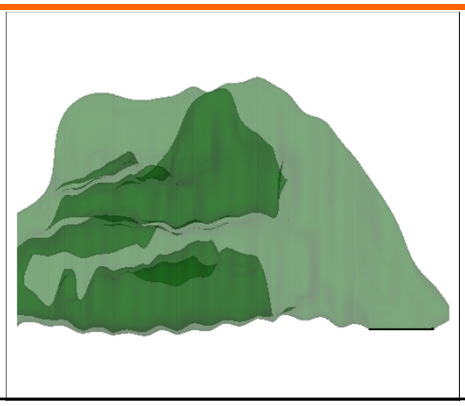

NASAL MODEL

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Comparison of Captrue Efficiency with Experimental Data

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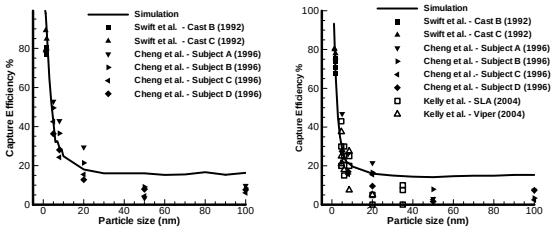
Ultra fine Particles



4 L/min

10 L/min

Nosal Captrue Efficiency Versus Peclet Number

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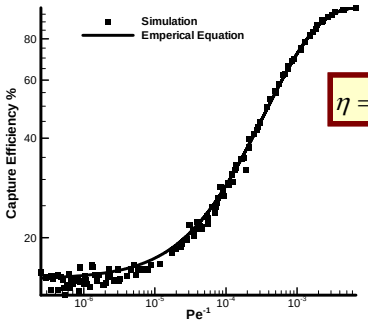
Ultra fine Particles



$$\eta = 100(1 - 0.85e^{-280Pe^{-0.8}})$$

$$Pe = \frac{Q}{DL}$$

Nose Deposition

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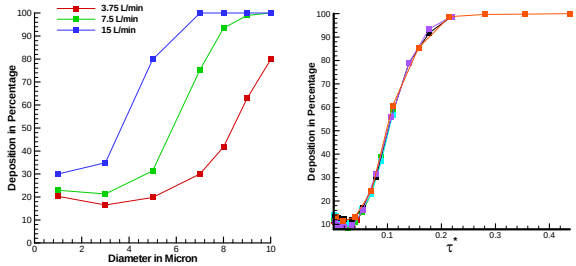

Deposition Efficiency

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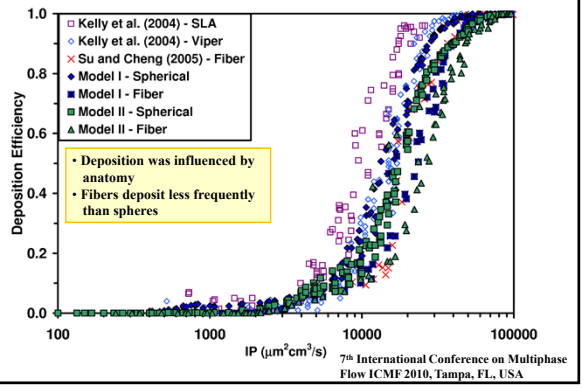

7th International Conference on Multiphase Flow ICMF 2010, Tampa, FL, USA

Septal Deviation

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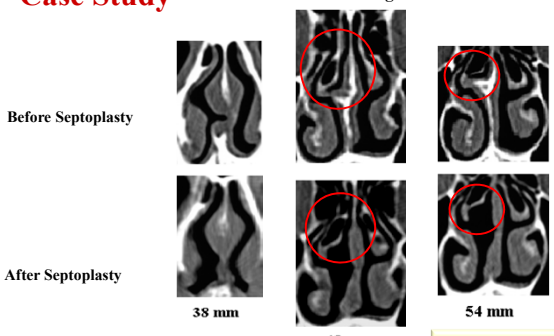
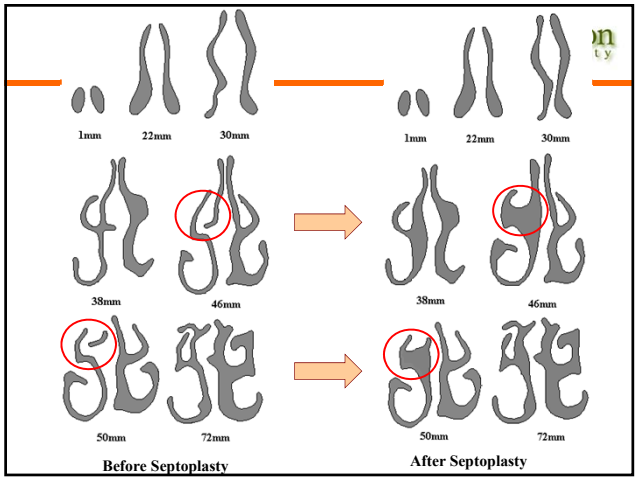
Case Study

CT Scan Images



Abouali et al. (2012)



Passage Cross Section Areas

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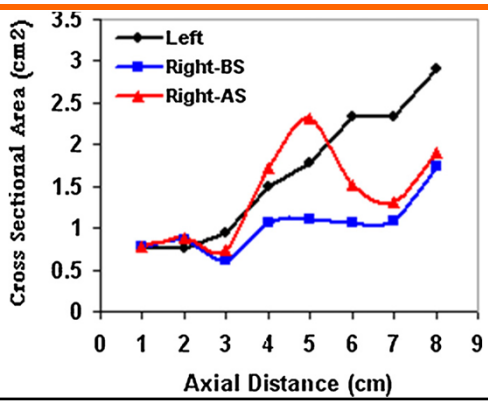

Flow Pattern

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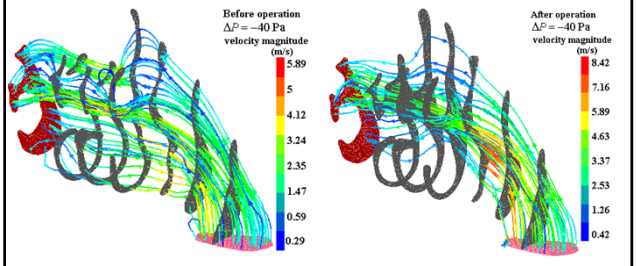

Before Operation

After Operation

Flow Rate-Pressure Drop

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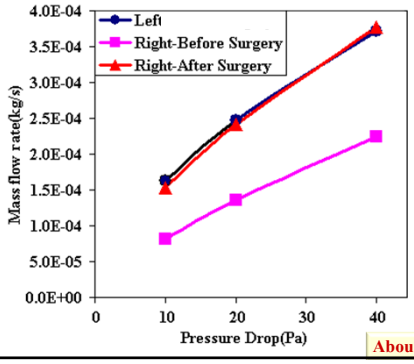

Abouali et al. (2012)

Comparison of Airflow Fields

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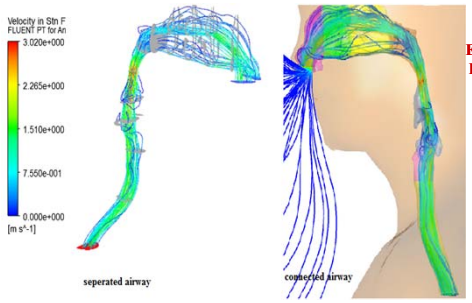

Effect of Thermal Plume and facial features

Q=7 L/min

The stream lines of the airflow (colored by velocity magnitude

Temperature Contours

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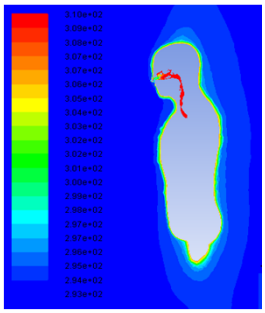

Air temperature =20°C

Mannequin surface temperature = 34°C

Particle Concentration at Nostril

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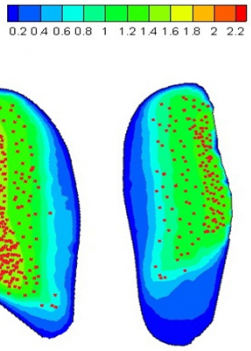

Resuspension Due to Walking

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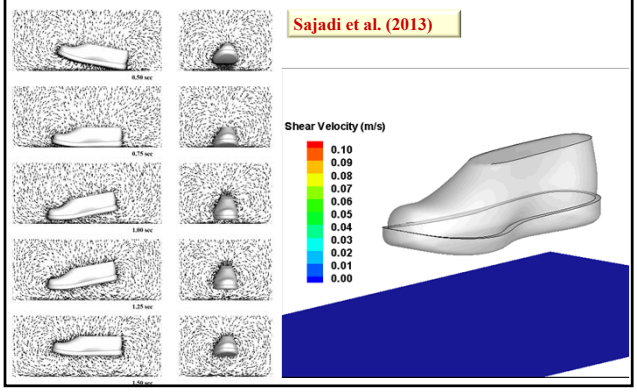

Airflow and Pollutant Transport in a Room

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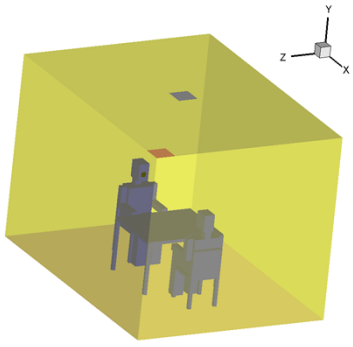
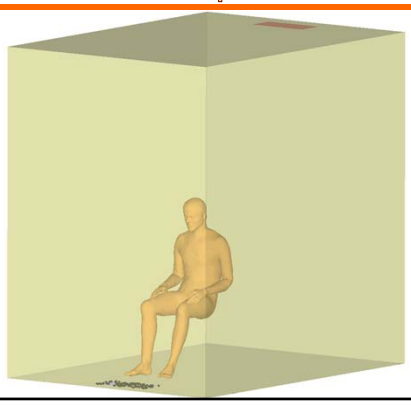


Airflow and Pollutant Transport in a Room

Clarkson University



Airflow and Pollutant Transport in a Cabin

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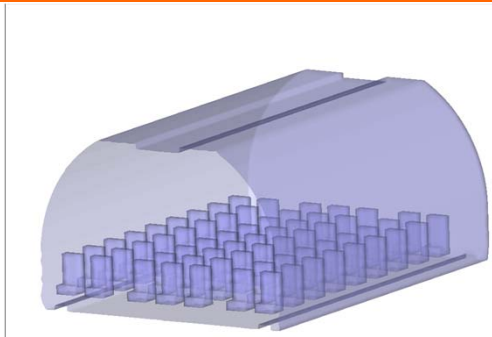

DNS of Turbulent Channel Flow

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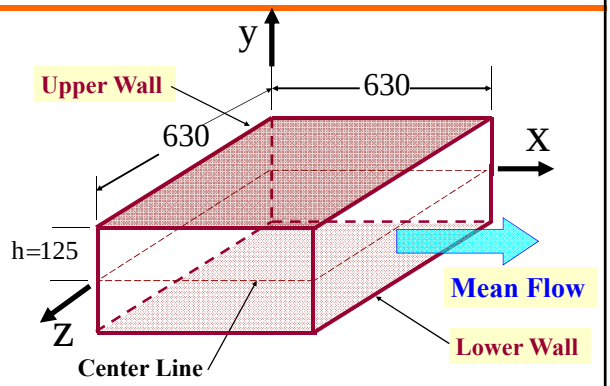

Sample Velocity Vector Plots

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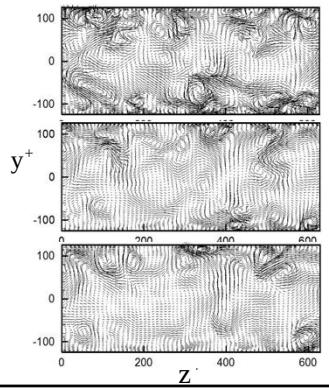

One-way coupling

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

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

Deposition Pattern

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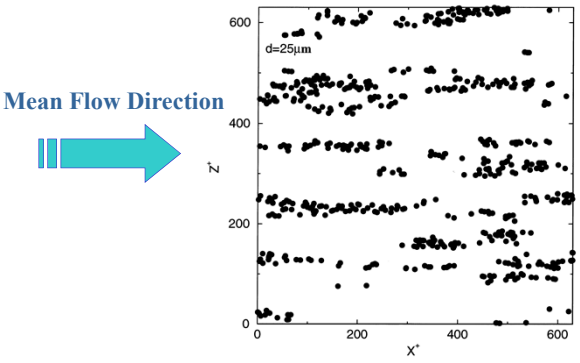
Mean Flow Direction



Coherent Wall Vorticies

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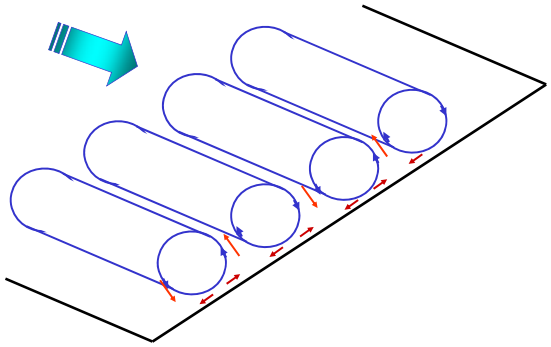

Particle Deposition Velocity

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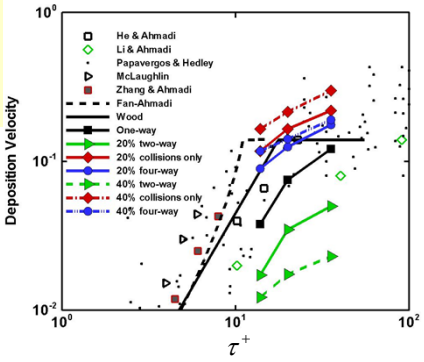
- Effect of Mass Loading
- Two-Way Coupling
- Particle Collisions
- Four-Way Coupling

u_d^+



Conclusions

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- Using fundamentals of multiphase flows provides a better understanding of environmental and biomedical systems
- Computational modeling helps in optimizing industrial processes

Collaborators

Clarkson University

- 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

Thank You!
Questions?

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