Numerical modeling of particle filtration in porous media

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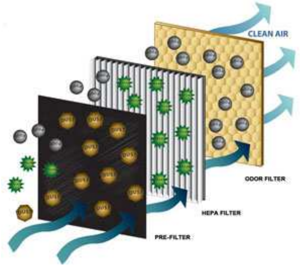
Removal efficiency and inertial effects



http://www.achooallergy.com/images/alen-particle-filtration.jpg

Motivation

- Quantify sensitivity of droplet deposition to
  - the flow conditions
  - particle size
  - the inner structure of the porous medium
- Application: Estimation of removal efficiency of various porous filters

$$\mathbf{E}(\text{removal rate}) = \frac{N_{out}(\text{number of droplets at the output})}{N_{in}(\text{number of droplets at the input })}$$

Outline

1. **Introduction**
2. Gas flow and droplet motion
3. Structured porous media
4. Conclusions & Outlook

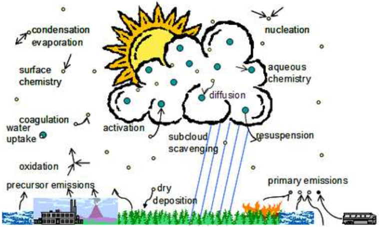
Aerosol droplets and particles

Minute particulate bits of solid or liquid material suspended in the air.

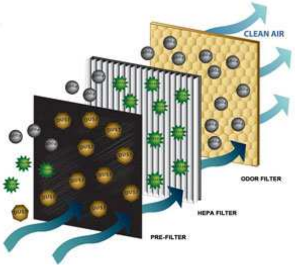
Sources

- Natural:
  - dust from dry regions blown by the wind
  - released by erupting volcanoes or forest fires
  - salt & droplets from the ocean
- Result of industrial activities:
  - by burning fossil fuels
  - by burning wood

Aerosols



http://www.pnl.gov/atmospheric/research/aci/images/aerosol_clouds.jpg



http://www.achooallergy.com/images/alen-particle-filtration.jpg

http://www.keepbanderabeautiful.org/smog-los-angeles.jpg

http://www.instablogsimages.com/images/2008/01/24/designer-bookshelf-by-marc-newson_5906.jpg

Filtration mechanisms

- Interception
- Inertial impaction
- Diffusion
- Gravitational settling
- Electrostatic attraction

Filtration mechanisms

- Interception
- Inertial impaction: Essential for large particles
- Diffusion: Essential for small particles
- Gravitational settling
- Electrostatic attraction

Experimentally obtained expressions are known for efficiency of each mechanism

Outline

Our approach: Euler-Lagrangian modeling

- Fluid is treated as a continuous phase (Eulerian approach)
- Droplets are treated as discrete phase (Lagrangian approach)

  \+ variety of forces can be considered directly
  \- requires simulation of large number of particles to obtain deposition profiles ⇒ computationally expensive

Alternative approach: Euler-Euler modeling

- Droplets are treated as continuous phase

  \+ easy to simulate large particle counts
  \- requires complex closure modeling to adopt variety of forces

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Gas phase

- Governing equations for the gas phase:

$$\nabla \cdot \mathbf{u} = 0 \tag{1a}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{\mathrm{Re}} \nabla^2 \mathbf{u} + \mathbf{f} \tag{1b}$$

where

* **u** fluid velocity
* p pressure
* Re Reynolds number
* **f** body force representing solid porous medium: Penalization of gas to enter solid porous matrix material

Particle phase

- Governing equations for the particle phase:

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}(t) \tag{2a}$$

$$\frac{d\mathbf{v}}{dt} = \frac{1}{\tau}(\mathbf{u}(\mathbf{x}(t), t) - \mathbf{v}(t)) + \text{Brownian motion} \tag{2b}$$

where

* $\mathbf{x}$ particle position
* $\mathbf{v}$ particle velocity
* τ Stokes relaxation time

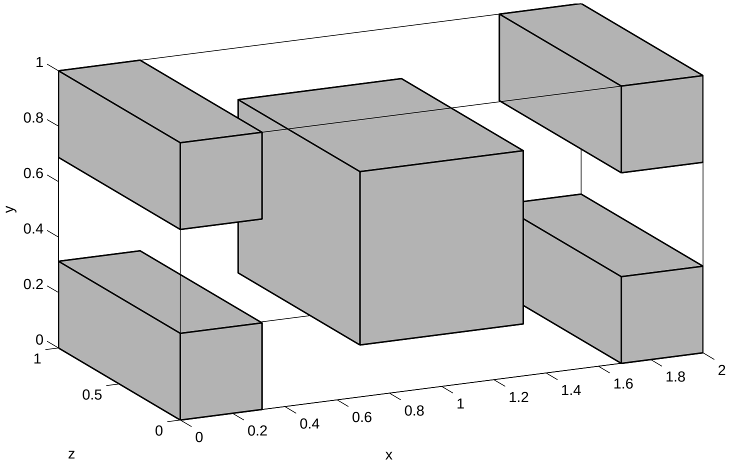
- Maxey-Riley equations restricted to the dominant Stokes drag

Numerical treatment

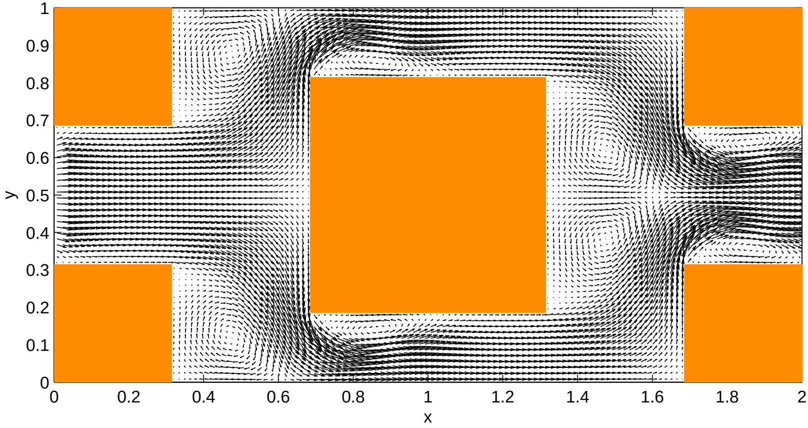
- Gas phase: Skew-symmetric finite volume discretization method
- Porous media: Immersed boundary (IB) method with volume penalization forcing by using masking function **H**
  - $\mathbf{H} = \begin{cases} 1 & \text{inside the solid} \\ 0 & \text{otherwise} \end{cases}$
- Particle phase: First order time integration, trilinear interpolation of fluid velocity at particle position
- Filtration: Particle is filtrated if it "enters" a region with **H**=1
- Verified: Overall first order convergent methods

Outline

Model porous media: Periodic arrangement of staggered square rods in 3D



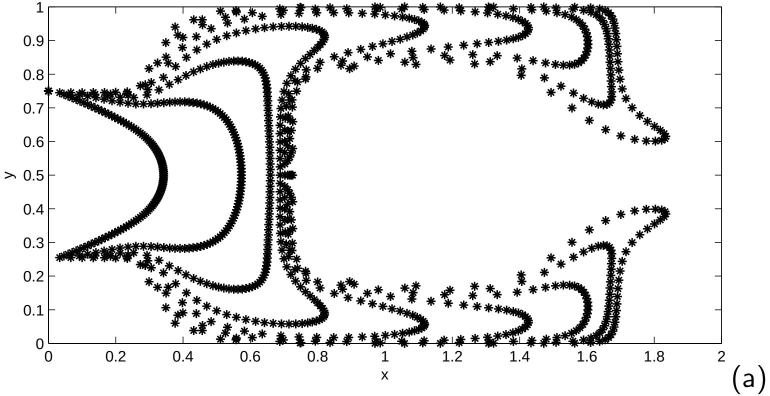
Simulated velocity vectors for Re=100



Filtration

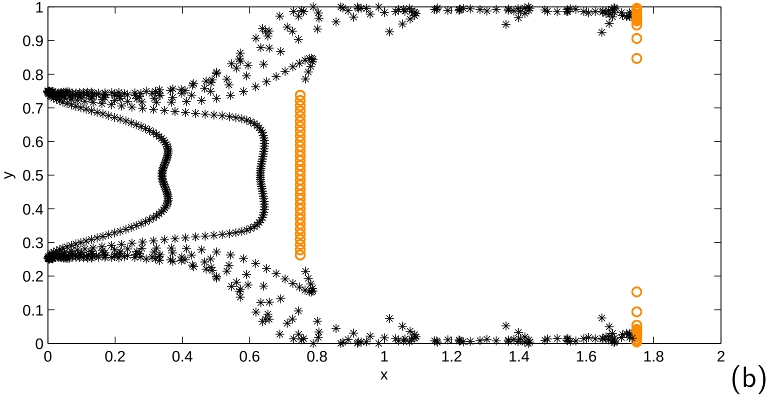
- An ensemble of particles embedded in the model porous media (with random or structured initial positions)
- Initial velocities of particles: Velocity of the fluid interpolated at particle position
- Use masking function **H** to assess whether the particles are filtrated/unfiltered
- Determine removal rate **E** as a function of time and Stokes number

Particle trajectories



(a) $\tau = 0.05, Re = 10$

Particle trajectories: Particles in orange are captured



(b) $\tau = 0.05, Re = 100$

Filtration efficiency

- Determine removal rate **E** for a range of Stokes numbers
- Removal coefficient γ given by the removal rate **E**
- Determine γ as a function of Stokes number

Outline

Conclusions

- Euler-Lagrange approach is developed for describing microscopic behavior of droplets inside the porous filter
- The decay of unfiltered particles follows an exponential trend
- For considered cases of Reynolds number an increase in the droplet inertia implies an increase in the filtration efficiency
- For some values of Reynolds number a non-monotonic behavior is observed - related to the structured nature of the model porous medium ?!

Outlook

- Include Brownian diffusion effect for low Stokes numbers
- Parameter study for filtration efficiency of realistic filters
- Data can be used in order to improve drift-flux models in Euler-Euler framework