



**COUPLING OF OPENFOAM AND
OPEN DYNAMICS ENGINE
TO DESCRIBE DUST TRANSPORT AND DEPOSITION IN A
TURBULENT ATMOSPHERIC FLOW**

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Outline

Motivation

Method

- Open Dynamics Engine

- Adding parallelism to Particle code

- Coupling ODE and OpenFOAM

- Forces acting on particles

Method and validation

- Stokes drag

- Brownian force effect

- Turbulence dispersion effect

Example of practical usage

Summary

Motivation



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In desert and semi-desert regions like Middle East and North Africa or China's Gobi desert sand and dust particles (typically with diameters D in the range of $0.1-100 \mu\text{m}$) strongly affect environmental processes, machinery and human health.

E.g., dust storms, can paralyze city's infrastructure or can cause problem with the health.

Insgesamt können in Abhängigkeit von der Partikelgrösse drei Feinstaubkategorien unterschieden werden:

- 1 **Inhalierbarer Feinstaub** mit Durchmesser von 2.5 - 10 μm wird etwa bis zum Kehlkopf bzw. zur Luftröhre eingeatmet.

Nasen-Rachenraum	5-10 μm
Luftröhre	3-5 μm

- 2 **Lungengängiger Feinstaub** 1 - 2.5 μm gelangt über Luftröhre und Bronchien tief in die Lunge hinein.

Bronchien	2-3 μm
Bronchiolen	1-2 μm

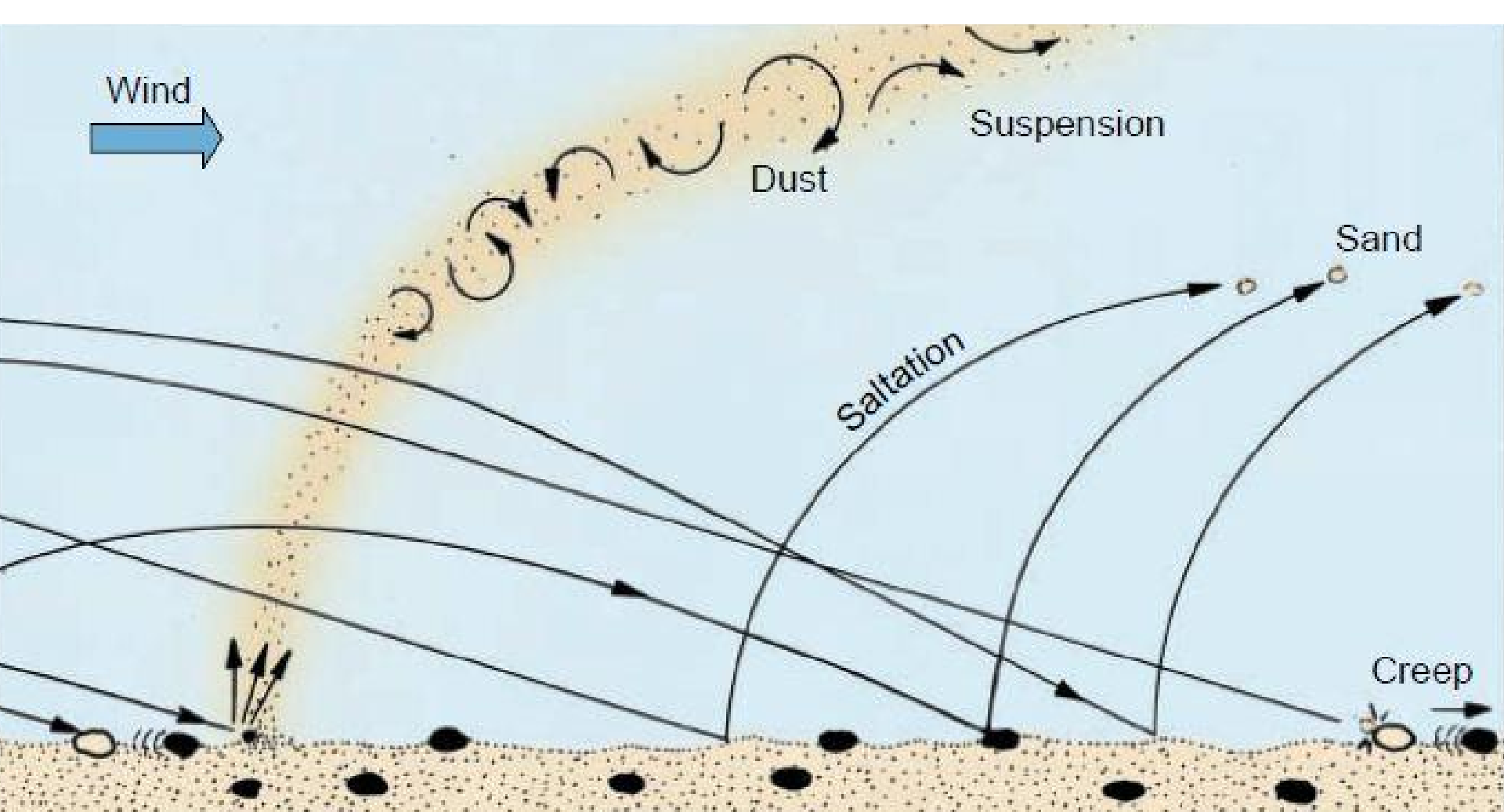
- 3 **Ultrafeine Partikel** kleiner als 1 μm dringen bis in die Alveolen vor, werden von dort nur sehr langsam oder gar nicht wieder entfernt und gelangen z.T. sogar in die Blutbahn.

Alveolen (Lungebläschen)	0.1-1 μm
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Trachea

Bronchi

Alveoli





Nile River

Red Sea



Common characteristics which are inherent for above mentioned examples:

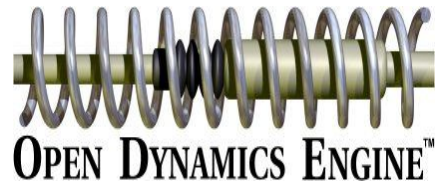
- force field, which determines the motion of the particles;
- huge amount of particles;
- interparticle interaction and collisions with walls;
- shape of the particles can be complex;
- The dispersed phase can exchange momentum with the fluid phase.

Method and validation

We developed a computational framework which couples two open source codes:

1. Particle code (*Open Dynamics Engine (ODE)*)
2. CFD code (*OpenFOAM*)

Open  FOAM
The Open Source CFD Toolbox



To describe the motion of the fluid phase in the presence of a particulate phase the modified set of Navier-Stokes Equations is used:

$$\frac{\partial \alpha_f \rho_f}{\partial t} + \nabla \cdot (\alpha_f \rho_f \mathbf{u}_f) = 0$$

$$\frac{\partial (\alpha_f \rho_f \mathbf{u}_f)}{\partial t} + \nabla \cdot (\alpha_f \rho_f \mathbf{u}_f \mathbf{u}_f) = -\alpha_f \nabla p + \nabla \cdot (\alpha_f \boldsymbol{\tau}_f) + \alpha_f \rho_f \mathbf{g} - \mathbf{f}_{drag}$$

$$\alpha_f = 1 - \sum_{k=1}^{n_p} V_{pk} / \Delta V, \quad \mathbf{f}_{drag} = \frac{1}{\Delta V} \sum_{i=1}^{n_p} \mathbf{F}_{drag,i}$$

α_f – fluid volume fraction;

\mathbf{u}_f – fluid velocity;

ρ_f – fluid density;

p – pressure;

$\boldsymbol{\tau}$ – stress tensor;

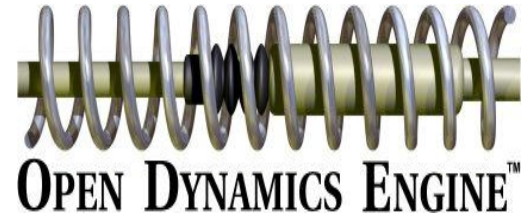
V_{pk} – volume of k -particle;

n_p – number of particles;

ΔV – cell volume;

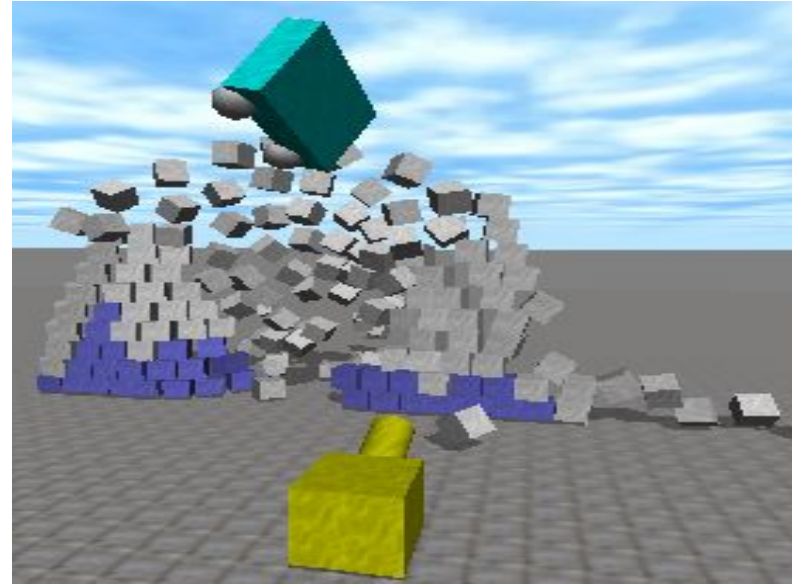
\mathbf{f}_{drag} – fluid-solid momentum exchange term.

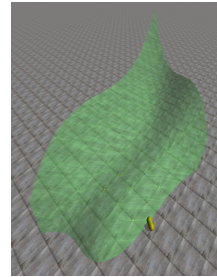
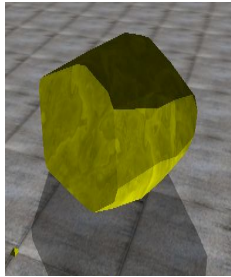
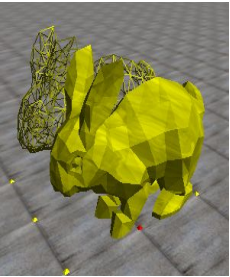
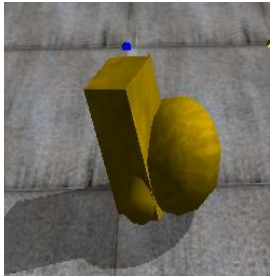
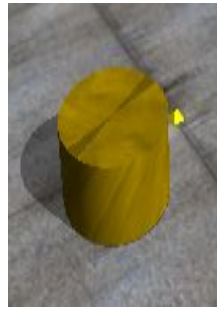
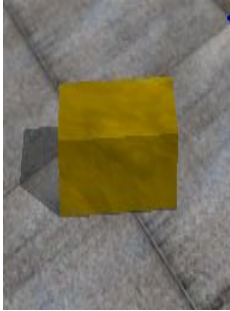
Open Dynamics Engine



The Open Dynamics Engine (ODE):

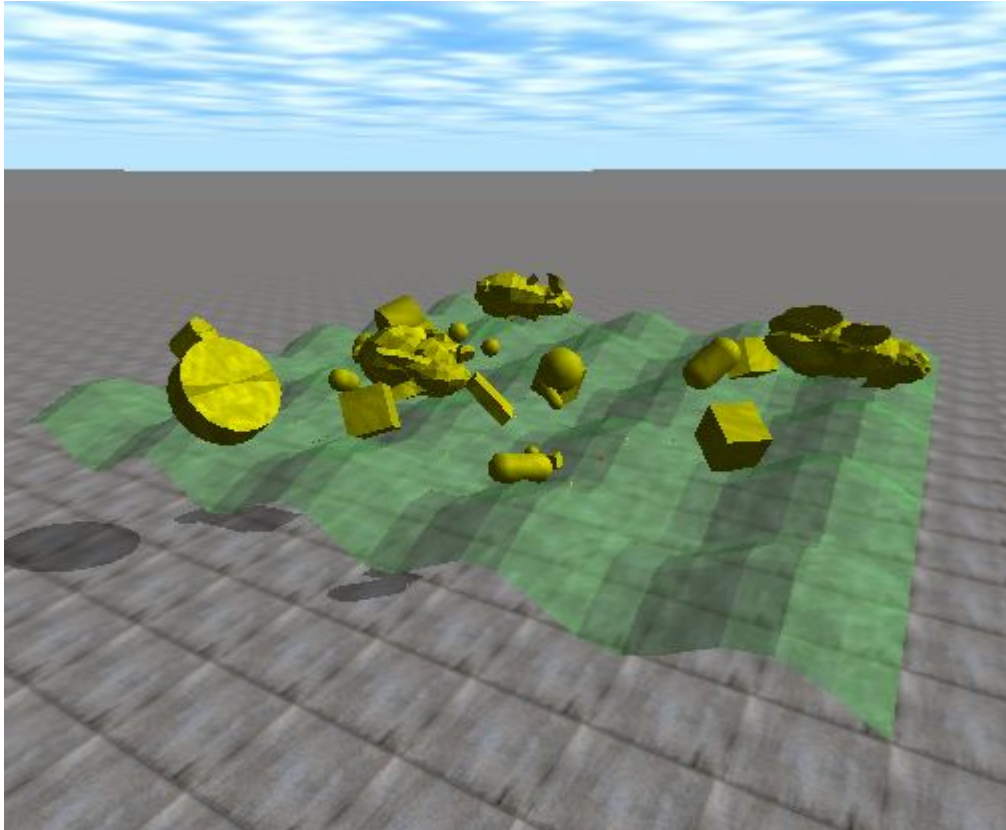
- rigid body dynamics;
- collision detection.





ODE supports different types of shapes:

sphere, box,
capsule, cylinder,
composite body,
triangle mesh, convex body,
height field.

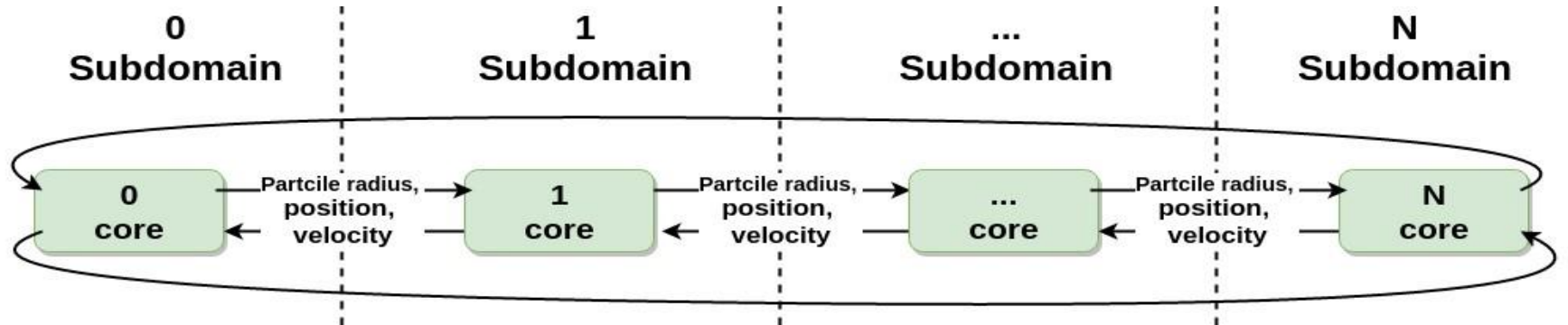


ODE resolves collisions between these objects of different shape.

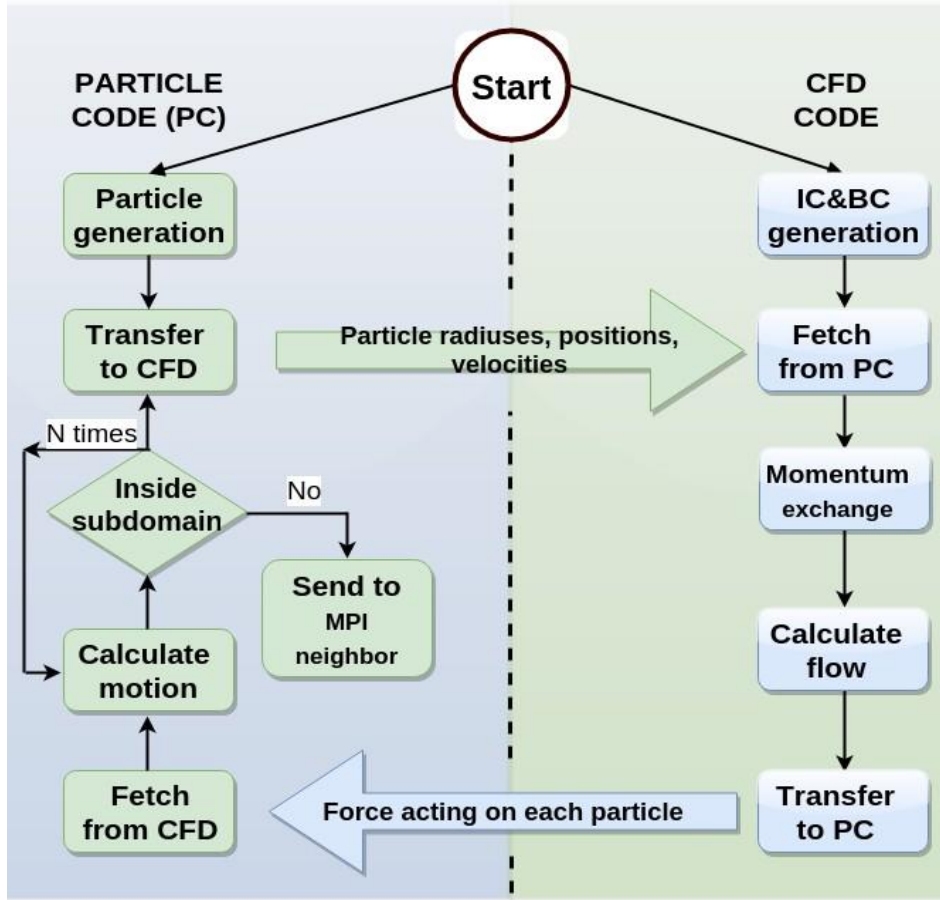
BUT! By default ODE does not supports distributed memory parallelism.

Adding parallelism to Particle code

To run developed coupled model on distributed memory machines we have implemented an ability of particles transfer between computing cores using MPI communication protocol.



Coupling ODE with OpenFOAM



- 1) Particles properties are transferred to the CFD part;
- 2) For each CFD cell, the volume fraction is determined;
- 3) The momentum exchange term between the airflow and particles is evaluated;
- 4) Fluid flow is calculated;
- 5) The forces acting on the particles are calculated and sent to the Particle part;
- 6) The Particle part calculates new particles positions using updated velocities and resolves collisions.

Forces acting on particles

Stokes Drag

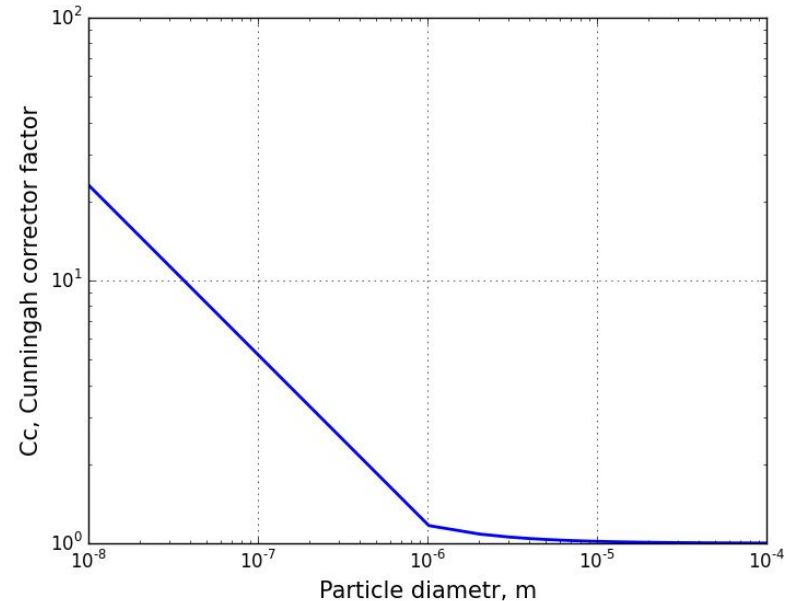
For the case of small spherical objects moving slowly through a viscous fluid Stokes derived an expression for the drag force:

$$F_{drag} = 3 \pi \mu v d_p / C_c$$

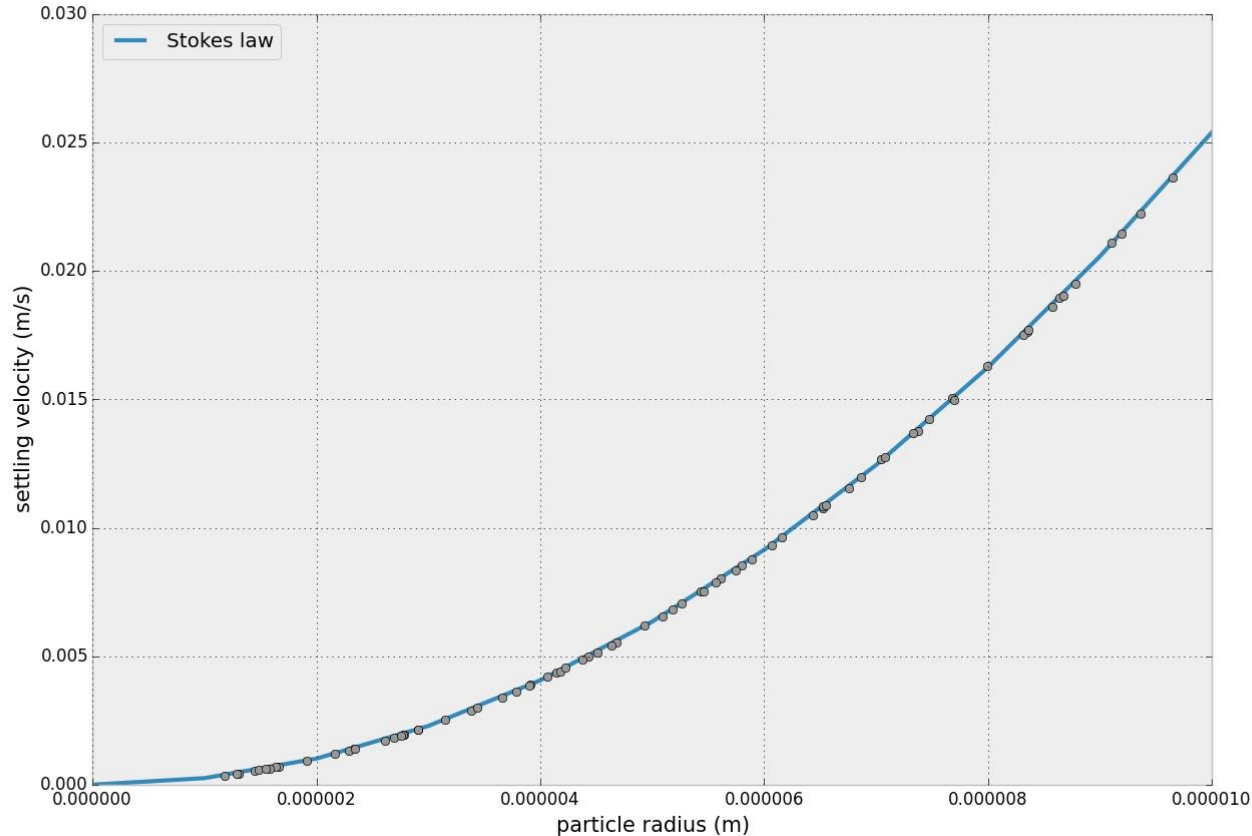
where C_c - Cunningham correction factor

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

λ - is the molecular mean free path of the gas molecules



Stokes drag. Validation.



Stokes deposition.
Comparison of
experimental data
(dots) with analytical
expression for settling
velocity (solid line):

$$v_t = C_c d_p^2 \rho_p / 18 \nu \rho_f$$

Brownian force

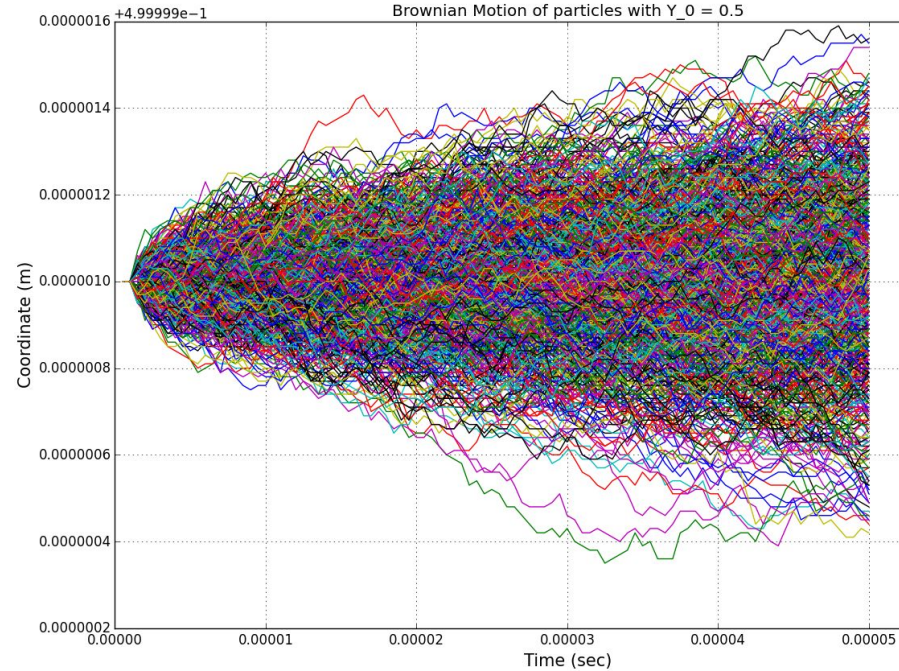
Small (<10 μm) particles.

Brownian force is modeled as a white noise stochastic process with intensity S_0 using:

$$S_0 = 216 \cdot \mu \cdot k_b \cdot T / (\pi^{1/2} \cdot d_p^5 \cdot \text{rhoRatio}^2 \cdot C_c)$$

The components of the Brownian force:

$$F_i = m_p \cdot \text{sqrt}(\pi \cdot S_0 / \Delta t) \cdot \text{Gauss}(\mu=0, \sigma=1)$$



Example of 10000 particle trajectories affected by Brownian force.

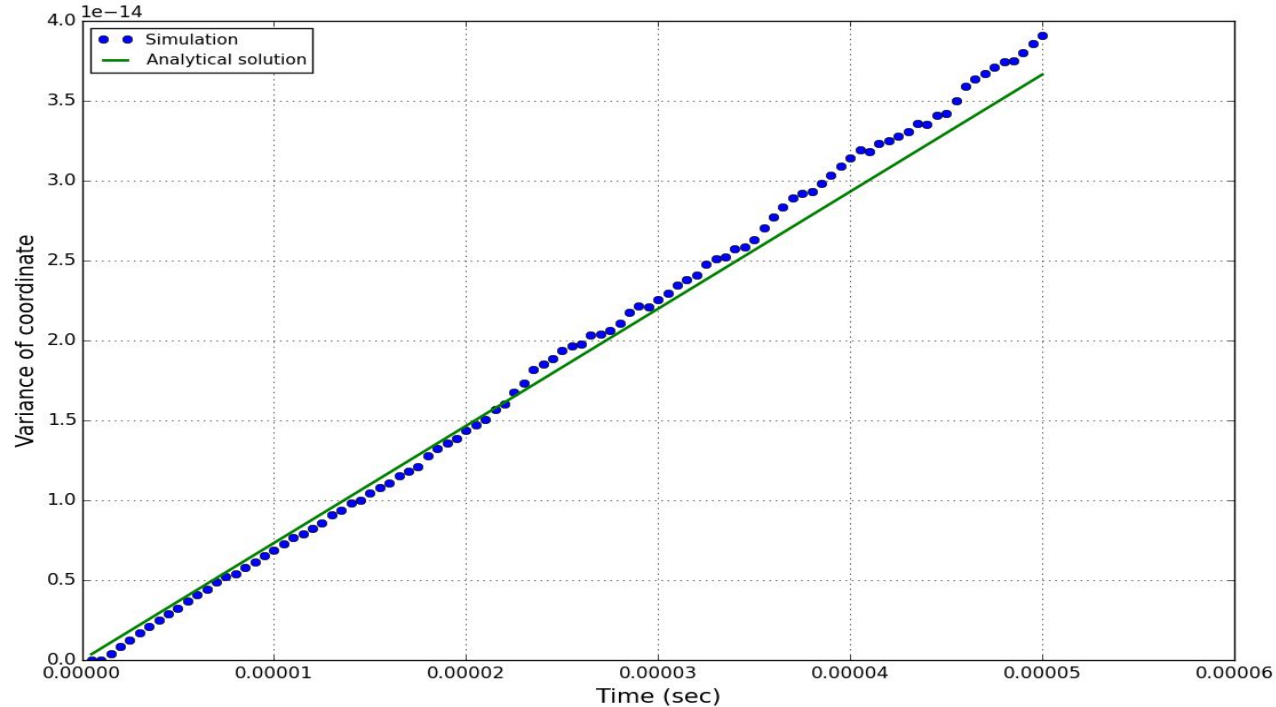
Brownian force. Validation.

Exact solution of the diffusion equation given as:

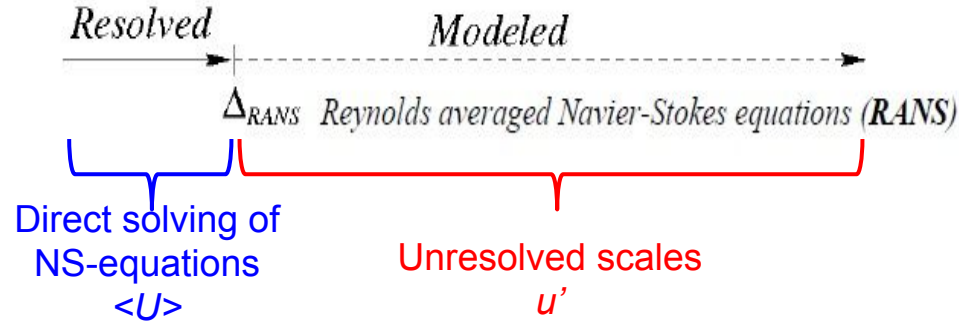
$$\sigma^2(t) = 2 \cdot D \cdot t,$$

where D - diffusion coefficient.

$$D = (k_b \cdot T_c \cdot C_c) / (2 \cdot \pi \cdot \mu \cdot d_p)$$



Turbulence dispersion effect



$$U = \langle U \rangle + u'$$

where

U - instantaneous flow velocity,

$\langle U \rangle$ - ensemble-averaged flow velocity,

u' - fluctuating velocity (turbulence).

To correctly describe particle movement within the turbulent flow the influence of **unresolved scales** on particle movement needs to be modelled!

Turbulence dispersion effect

To simulate the influence of **unresolved scales** on particles we use “**Stochastic model of particle dispersion**” (Gosman and Ioannides, 1983). This model is for homogeneous and isotropic turbulence.

Basic idea of the model:

1. Eval. of fluctuating fluid velocity $\mathbf{u}' = (2/3 k)^{1/2} \cdot \text{Gauss}(\mu=0, \sigma=1) \cdot (\text{random vector of unit length})$
2. Determ. of characteristic eddy size as $L_e = \rho C_\mu k^{3/2} / \varepsilon$, where $C_\mu = 0.09$
3. Eval. of interaction time (T_{int}) between particle and eddy depending on the particle relaxation time (τ) and relative velocity (U_{rel}) between particle and instantaneous flow.

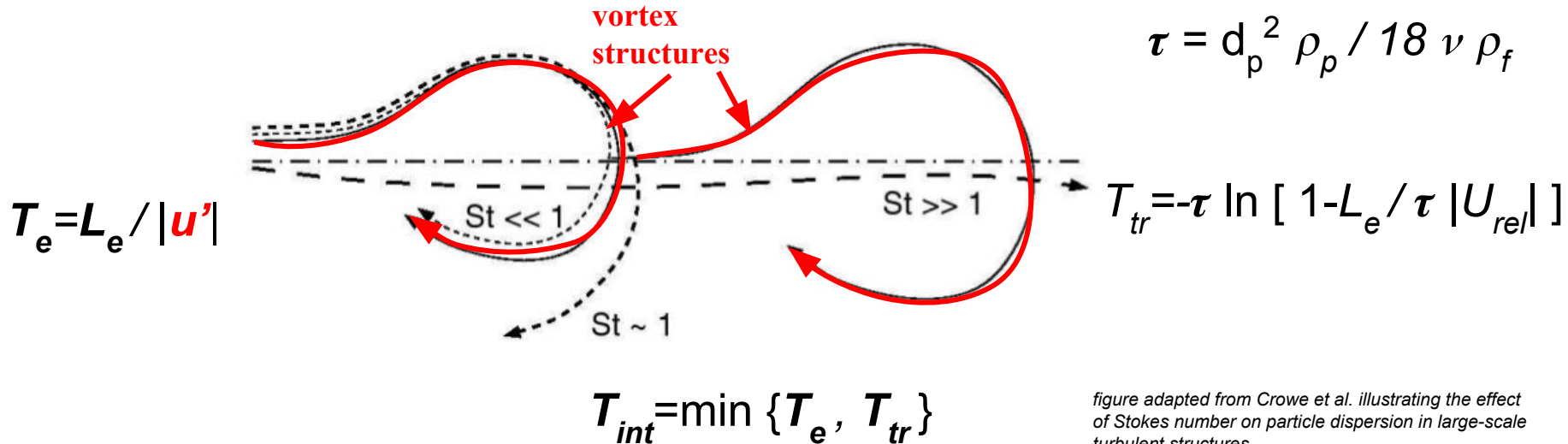


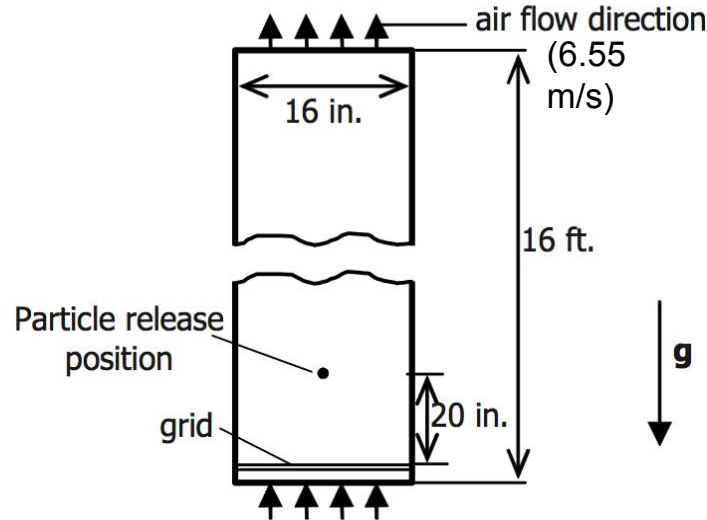
figure adapted from Crowe et al. illustrating the effect of Stokes number on particle dispersion in large-scale turbulent structures

Turbulence dispersion effect. Validation.

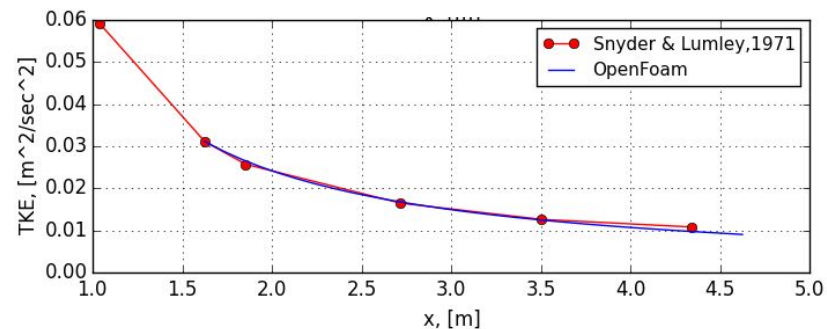
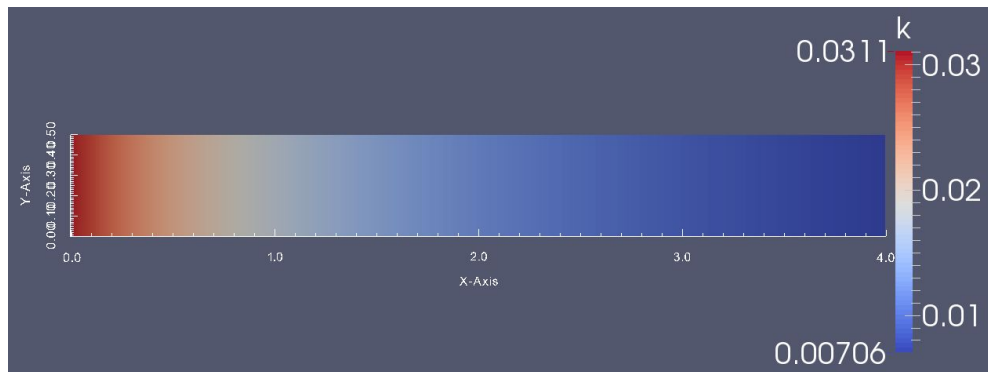
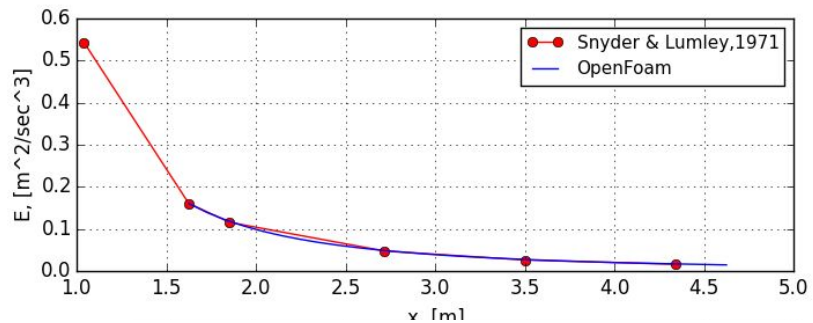
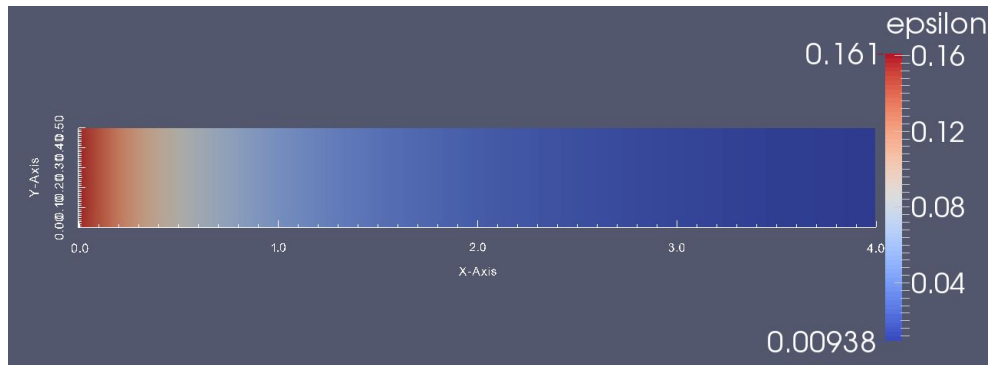
Model validation is based on experimental work of Snyder & Lumley, (1971).

They measured:

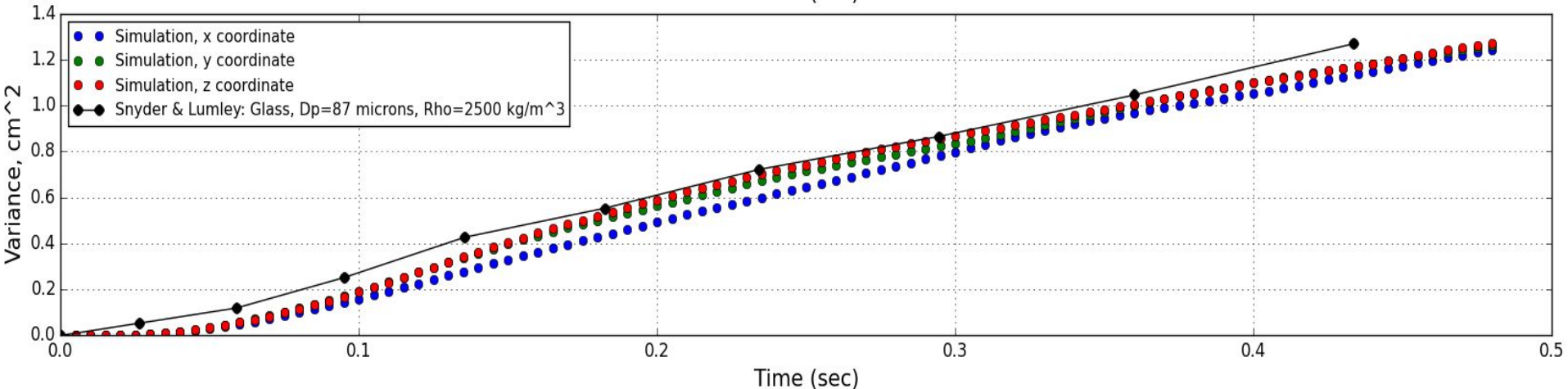
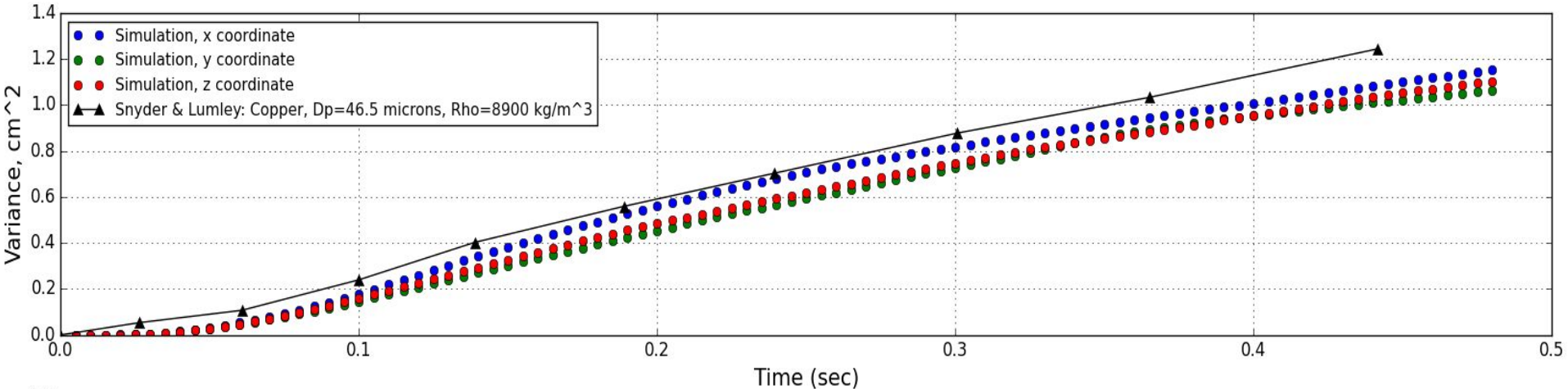
- particle horizontal displacement in a vertical homogeneous and isotropic turbulent flow.
- k and ϵ values along the flow.



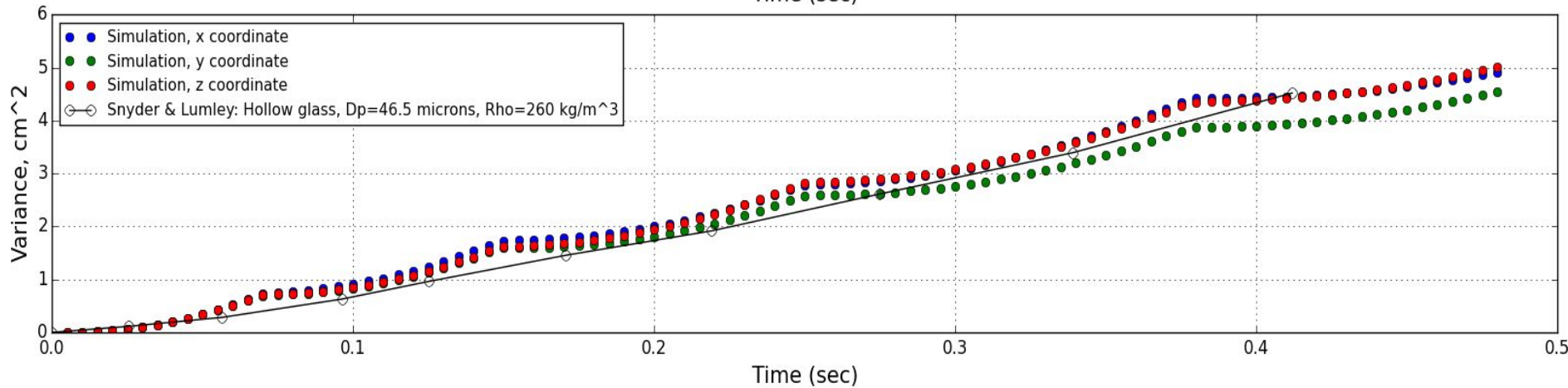
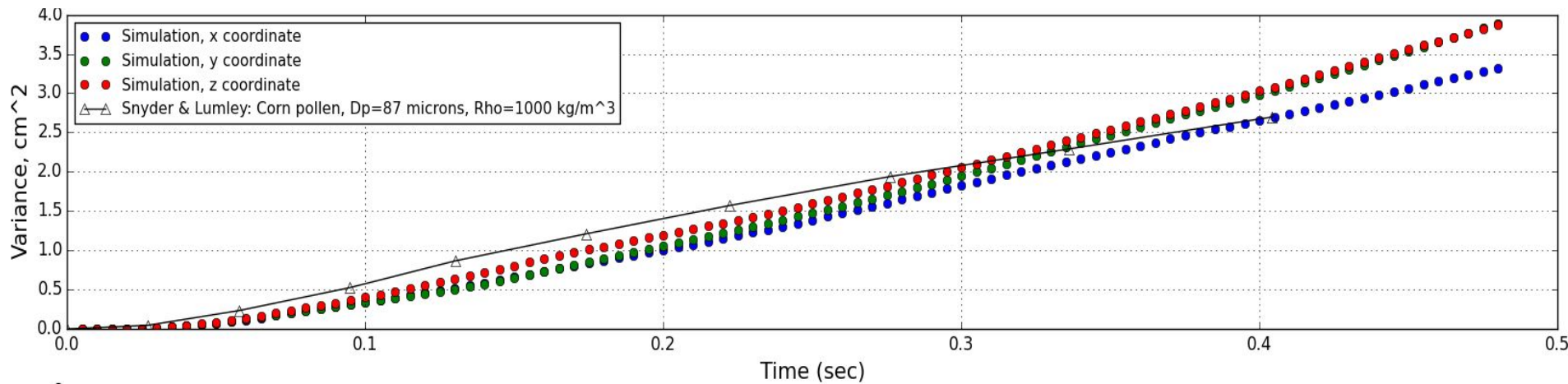
Turbulence dispersion effect. Validation.



Turbulence dispersion effect. Validation. Heavy particles.

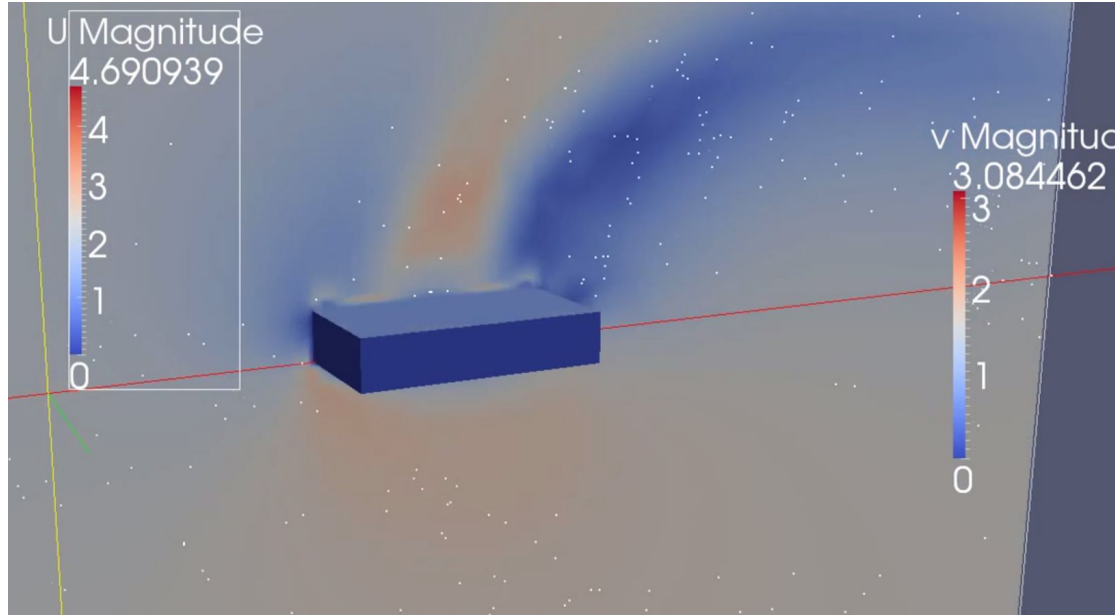


Turbulence dispersion effect. Validation. Light particles.



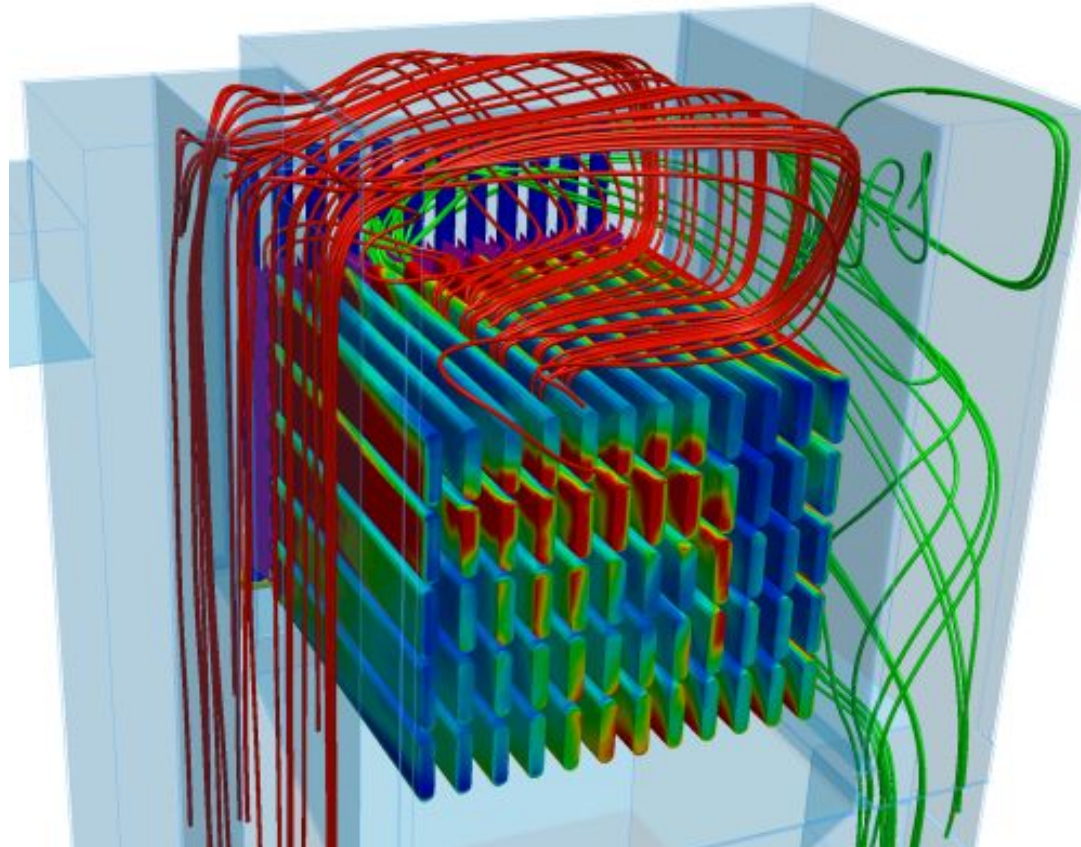
Example of practical usage

Simulation of dust deposition on solar panel with vibrating top surface.



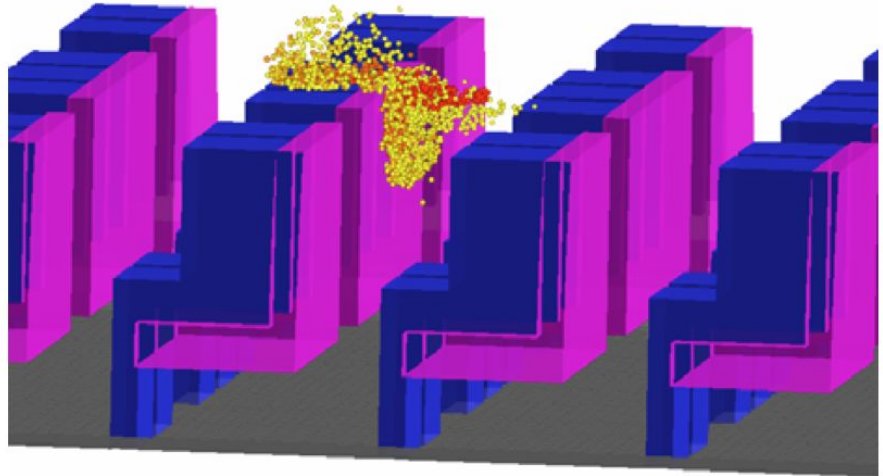
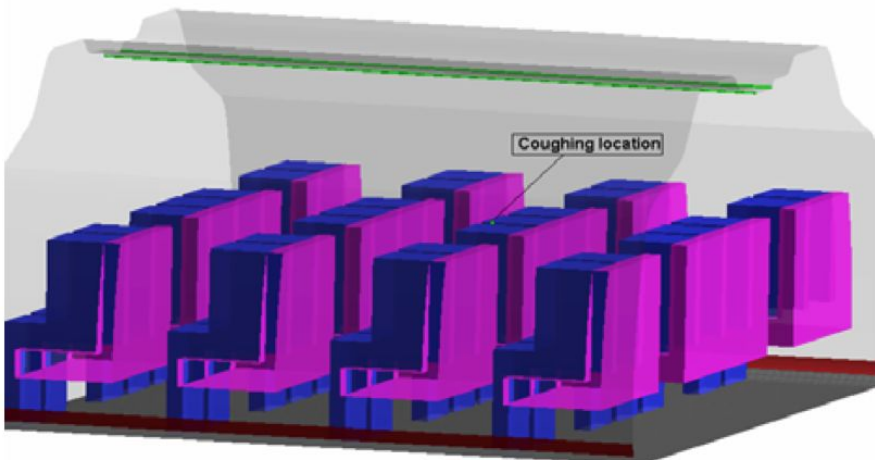
In its current configuration the model was applied for calculating dusty flows around a solar panel to evaluate dust effect on the panel's efficiency and test different approaches that allow to reduce deteriorating effects of dust on electricity generation.

Separation of particles inside air filter

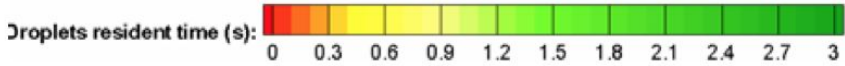


Droplets spreading in the aircraft cabin caused by coughing passenger

© PhD Thesis of Zhao Zhang, 2007



Current time: 0.53 (s) Coughing began at 0.0 (s) and finished at 0.5 (s).

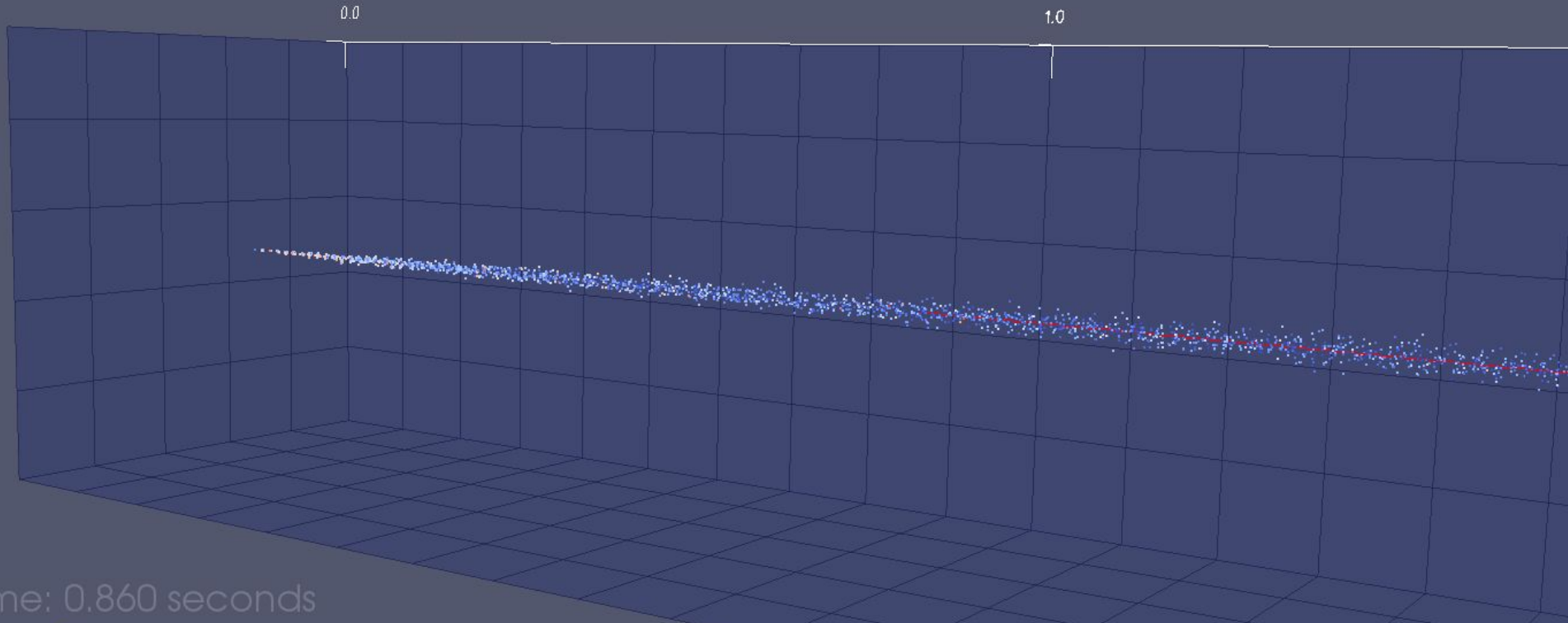


Summary

- Computational model which couples Open Dynamics Engine and OpenFOAM is developed;
- ODE is extended by parallel capabilities;
- Particle part of the code is validated against major effects;
- Example of practical model usage is demonstrated.

Thank you!

Turbulent dispersion of fluid particles. Based on Snyder & Lumley experiment (1971)



Disabled turbulent dispersion

