05-12-2019, Moscow, ISP RAS Open

Simulation of particle dynamics in planetary boundary layer and in a model wind farm

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ИСП РАН

Content

Introduction. The relevance of the topic

The tower observations

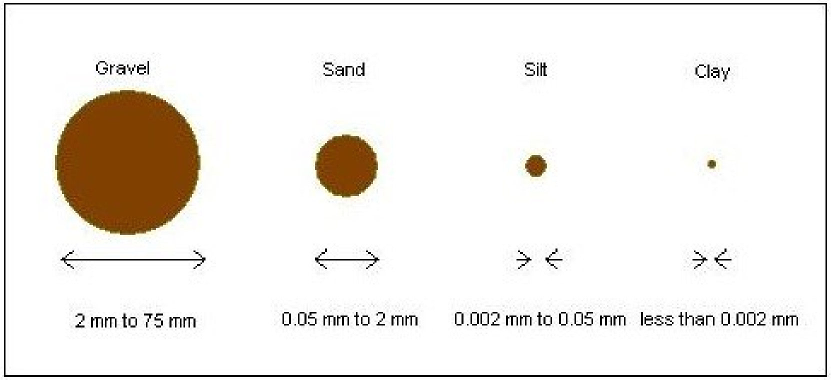
ABL (Atmosphere Boundary Layer) – layer with height of **2 km.**

The Goal: Studying of velocity wind profile, temperature, scalar transport, surface heat fluxes, diurnal cycles, particles

GABLS 1,2,3 (GEWEX Atmospheric Boundary Layer Study) project: Experiment and Simulation

Introduction. Different particles in ABL

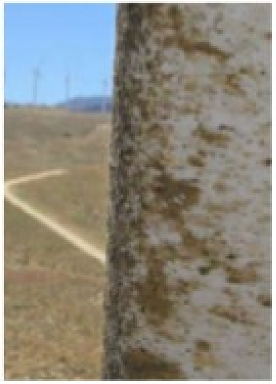
Soil Particle Size

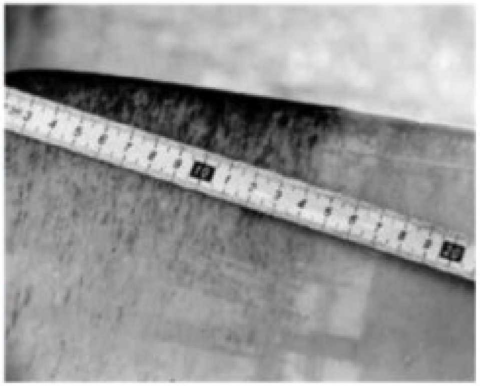


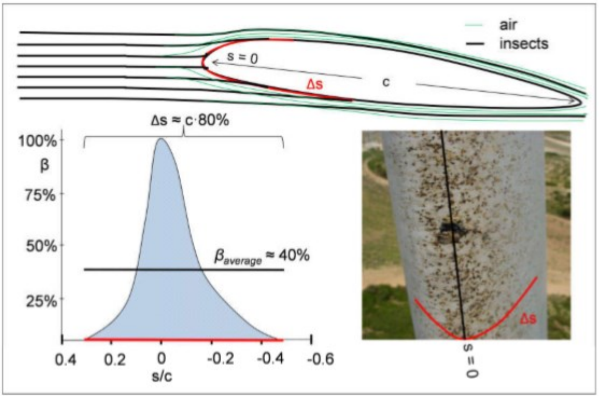
Small raindrops are 0.5-3mm in size

Larger raindrops are 4-6mm in size

Flying Insects (Hemiptera, Aphididae, Diptera, Hymenoptera, Coleoptera, others)







Mathematical formulation and parameters of a numerical model (ABL)

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0$$

$$\frac{\partial \bar{u}_i}{\partial t} = -\frac{\partial}{\partial x_j}\left(\bar{u}_j \bar{u}_i\right) - \frac{\partial R_{ij}^{D}}{\partial x_j} - \frac{\partial \tilde{p}}{\partial x_i} - \left(\frac{\partial \tilde{p}}{\partial x_i}\right)^{d} + \left(1 - \frac{\bar{\theta}}{\bar{\theta}^{0}}\right) g_i + \epsilon_{ij} f^{c} \bar{u}_j + S_u$$

$$\frac{\partial \bar{\theta}}{\partial t} = -\frac{\partial}{\partial x_j}\left(\bar{u}_j \bar{\theta}\right) - \frac{\partial R_{\theta j}}{\partial x_j}$$

$$R_{ij}^{D} = -2\nu^{SGS} \bar{S}_{ij}$$

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$$

$$\nu^{SGS} = (C_s \Delta)^2 \left(2\bar{S}_{ij}\bar{S}_{ij}\right)^{1/2}$$

$$R_{\theta j} = -\frac{\nu^{SGS}}{Pr_t}\frac{\partial \bar{\theta}}{\partial x_j}$$

$$\frac{\partial R_{ij}^{D}}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(\nu^{SGS}\frac{\partial \bar{u}_i}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\left[\nu^{SGS}\left(\frac{\partial \bar{u}_j}{\partial x_i} - \frac{2}{3}\frac{\partial \bar{u}_k}{\partial x_k}\delta_{ij}\right)\right]$$

The gas phase equations

[13]. Sagaut P. Large eddy simulation for incompressible flows: an introduction. Springer, Berlin, 2002. p 426

Mathematical model of pisoFoamTurbine.ALM in SOWFA

$$\frac{\partial \overline{u}_j}{\partial x_j} = 0$$ - mass conservation equation

$$\overline{u}_j = u_j - u'_j$$ - velocity after procedure of filtration

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_j \overline{u}_i\right) = -2\varepsilon_{ijk}\Omega_j \overline{u}_k - \frac{\partial \widetilde{p}}{\partial x_i} - \frac{\partial}{\partial x_j}\left(R_{ij}^D\right) + \left(\frac{\rho_b}{\rho_0} - 1\right) g_i - \left\langle \frac{\partial p}{\partial x_i} \right\rangle + f_i$$ - momentum equation

ε_{ijk} - the alternating tensor,
Ω_j - Rotation Rate Vector for Earth,
$\widetilde{p}$ - Modified pressure variable,
R_{ij}^D - Fluid stress tensor.

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial u_j \overline{\theta}}{\partial x_j} = -\frac{\partial \tau_{\theta_i}}{\partial x_j}$$ - a potential temperature transport equation

Where $\overline{\theta}_j$ - the resolved-scale potential temperature, τ_j - is the SGS temperature flux

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Churchfield, M. J., Lee. S., Michalakes, J., Moriarty. P. J. A numerical study of the effects of atmospheric and wake turbulence on wind turbine dynamics. // Journal of Turbulence, 2012, v. 13(14), pp. 1-32

Actuator Line Model for wind turbine

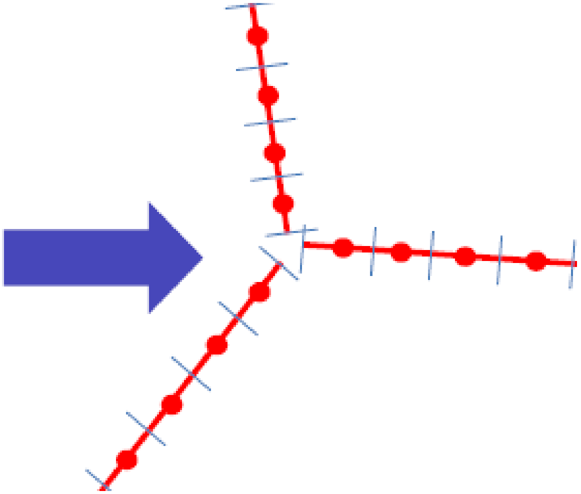


Figure . Wind turbine blade with points

$$f_i^{turbine}(r) = \frac{F_i^{actuator}}{\varepsilon^3 \pi^{3/2}} \exp\left[-\left(\frac{r}{\varepsilon}\right)^2\right]$$

Total Aerodynamic Force

Aerodynamics coefficients $Cx(\alpha)\ C_y(\alpha)$

Angle of Attack from -180 till 180. Simple bodies for wind turbine: "Cylinder1, "Cylinder2", airfoil profiles "DU40_A17", "DU35_A17", "DU30_A17", "DU25_A17", "DU21_A17", "NACA64_A17"

The Surface Shear Stress Model

$$u_*^2 = \sqrt{\left\langle \tau_{13S}(x,y) \right\rangle^2 + \left\langle \tau_{23S}(x,y) \right\rangle^2}$$

friction velocity

$$\left| \left\langle \overline{U}(z_1) \right\rangle \right| = \frac{u_*}{k} \left[\log\left(\frac{z_1}{z_0} \right) - \psi_m\left(\frac{z_1}{L} \right) \right]$$

Monin-Obukhov ABL similarity laws
(angle brackets denote planar average)

$$L = -u_* \frac{\theta_0}{kgq_s}$$

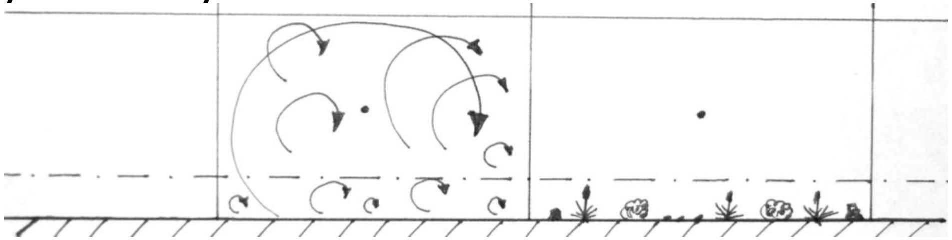
The Obukhov length

$$\tau_{i3S}(x,y) = -u_*^2 \frac{\overline{U}_i(x,y,z_1)}{\left| \left\langle \overline{U}(z_1) \right\rangle \right|}$$

The surface shear stress model of Schumann

Constraints

- Relies on planar averages (angle brackets)
- Mathematically valid only for flow over flat terrain



SGS turbulence surface roughness

Churchfield, M. J., Moriarty, P. J., Vijayakumar, G., Brasseur, J. G. Wind Energy-Related Atmospheric Boundary Layer Large-Eddy Simulation Using OpenFOAM. 19th Symposium on Boundary Layers and Turbulence. Keystone, Colorado, USA, 2 -6 August 2010. NREL

Mathematical model of motion of particles

$$\frac{\partial x_i^p}{\partial t} = u_i^p$$

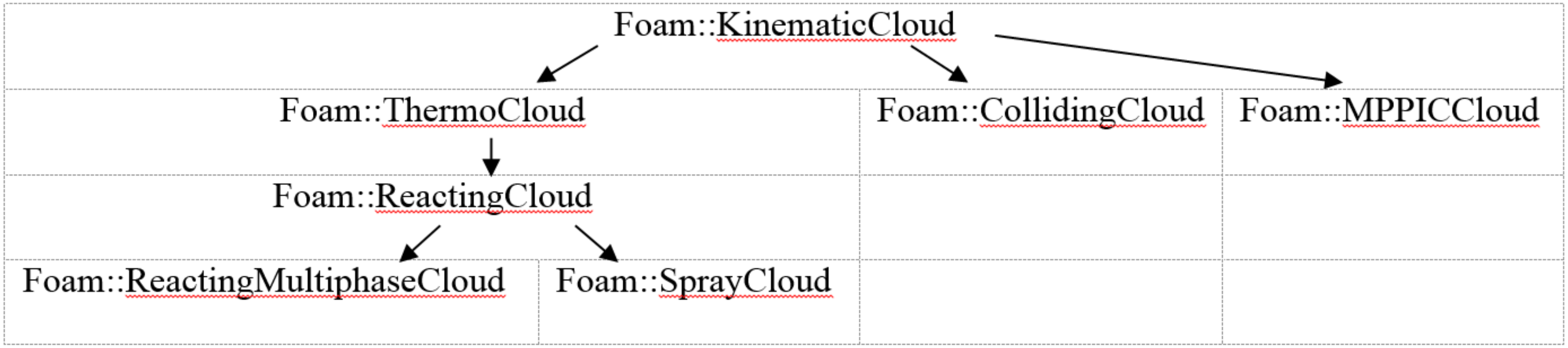
$$m_p \frac{\partial u_i^p}{\partial t} = F_i + F_g$$

$$F_i = \frac{1}{8}\pi d_p^2 \rho C_D \left(u_i - u_i^p\right)\left|u_i - u_i^p\right|$$

$$C_D = max\left(\frac{24\left(1+0.15Re^{0.687}\right)}{Re}, 0.44\right)$$

Development ABLSolverP

Main classes in OpenFoam with cloud of partciles



Foam::KinematicCloud

Foam::ThermoCloud

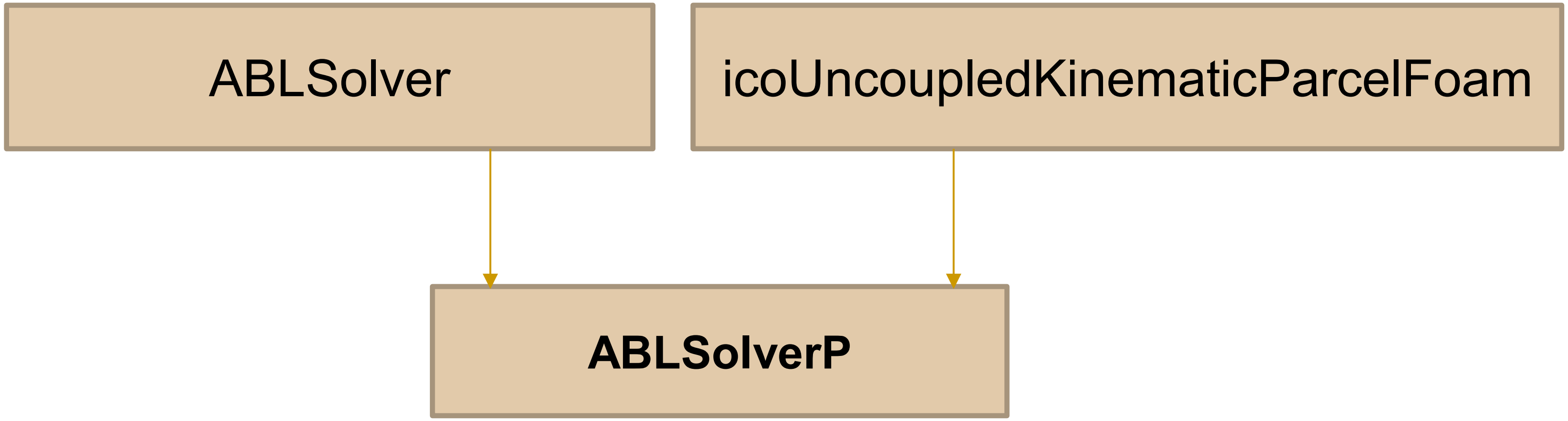
Foam::CollidingCloud

Foam::MPPICCloud

Foam::ReactingCloud

Foam::ReactingMultiphaseCloud

Foam::SprayCloud



ABLSolver

icoUncoupledKinematicParcelFoam

ABLSolverP

OpenFOAM software, SOWFA library and new solvers based on ABLSolver and pisoTurbineFoam.ALM

```
// Solve the momentum equation
    #include "computeCoriolisForce.H"
    #include "computeBuoyancyTerm.H"
fvVectorMatrixUEqn
    (
fvm::ddt(U)                             // time derivative
        + fvm::div(phi, U)              // convection
        + turbulence->divDevReff(U)     // momentum flux
        + fvc::div(Rwall)
        - fCoriolis                     // Coriolis force
        - SourceU                       // mesoscale source terms
- prho1 * kinematicCloud.SU(U)          // momentum form particles
    );
UEqn.relax();
```

ABLSolverP

OpenFOAM software, SOWFA library and new solvers based on ABLSolver and pisoTurbineFoam.ALM

```
// Momentum predictor
fvVectorMatrixUEqn
            (
              fvm::ddt(U)
              + fvm::div(phi, U)
              + turbulence->divDevReff(U)
              - turbines.force()
              - rrho1*kinematicCloud.SU(U)
            );
```

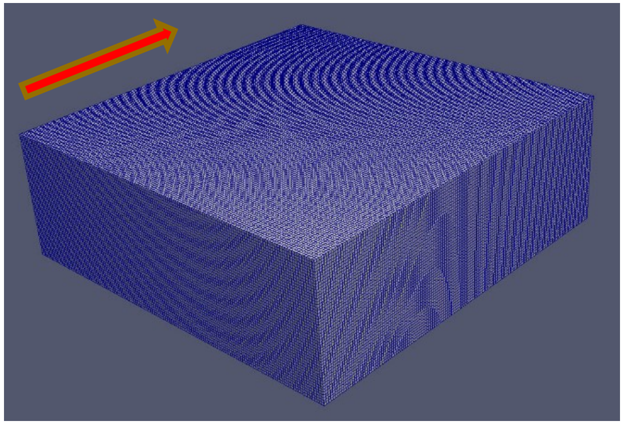
partpisoTurbineFoam.ALM

Neutral/Stable Stratification ABL test case

- Global Energy and Water Cycle Experiment Atmospheric Boundary Layer Study (GABLS) model intercomparison case
- Flat terrain
- 3000 m x 3000 m x 1020 m
- 150x150x51 grid (20 m) and 300x300x102 grid (10 m)
- Surface cooling rate 1.38889 K/s
- Periodic BCs
- Geostrophic wind U=8 m/s
- 54.19 N latitude
- z_0 =0.15 m
- SGS models:

Standard Smagorinsky

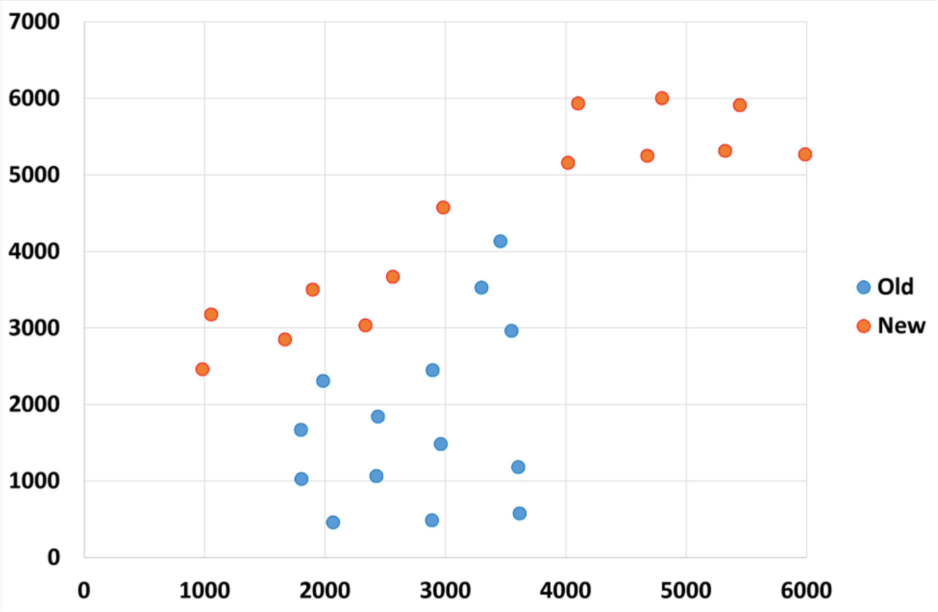
Dynamic Smagorinsky



Numerical domain and grid

The new wind farm of Ulyanovsk oblast of Russia

The territory of wind farm near the Volga River.

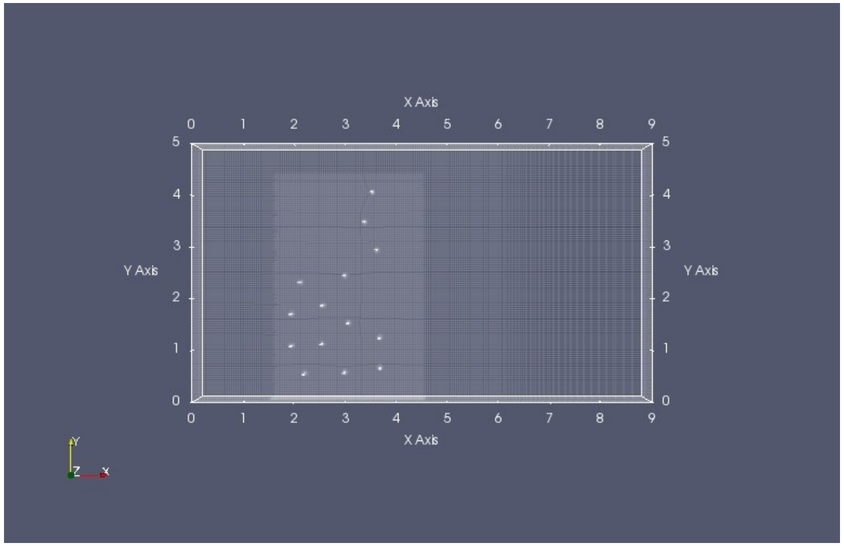


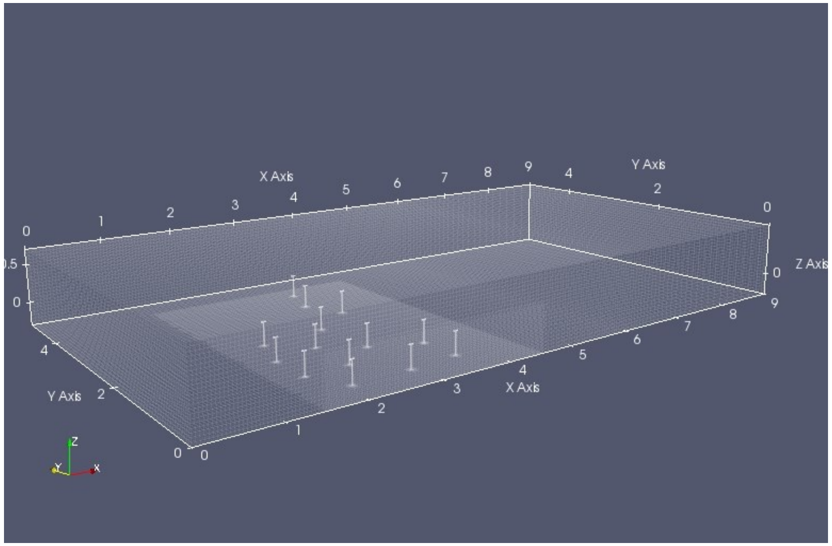
The wind farm with 28 wind turbines.

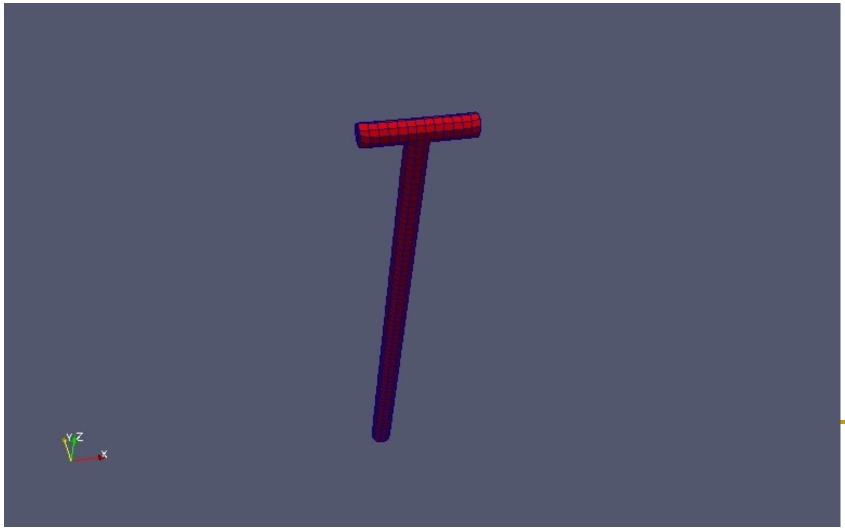
The wind farm has geographic coordinates N54° 17 ' E48° 08'.

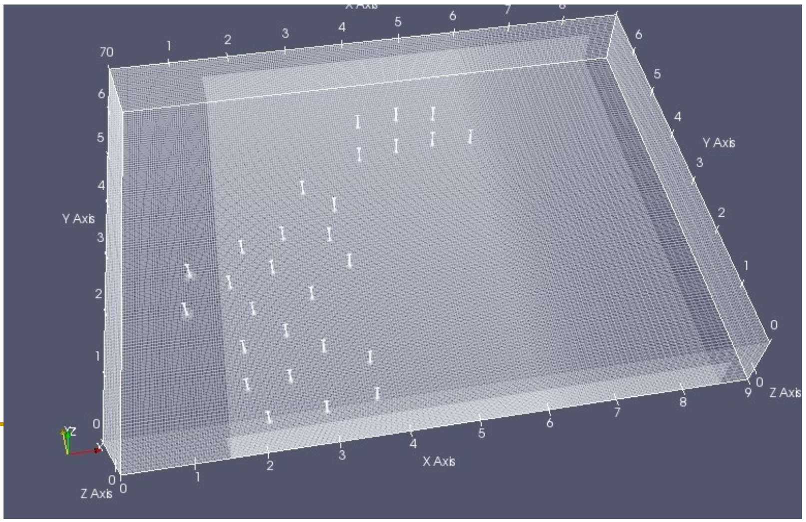
28 wind turbines: 14 with P=2.5 MW, 14 with P=3.6 MW

Numerical domain with 14 model wind turbines: the locations of wind turbines imitators are closed to wind farm in Ulyanovskya oblast of Russia

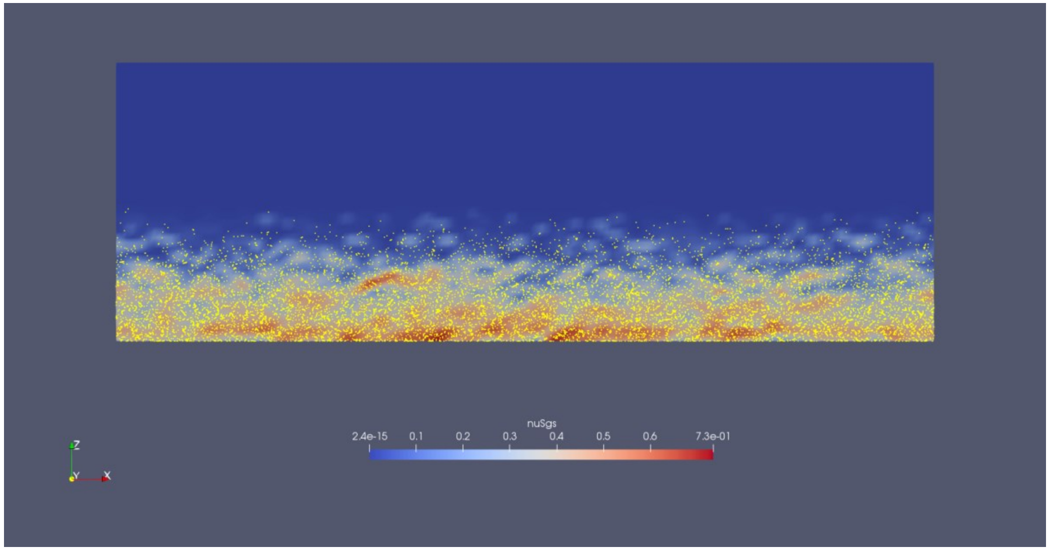








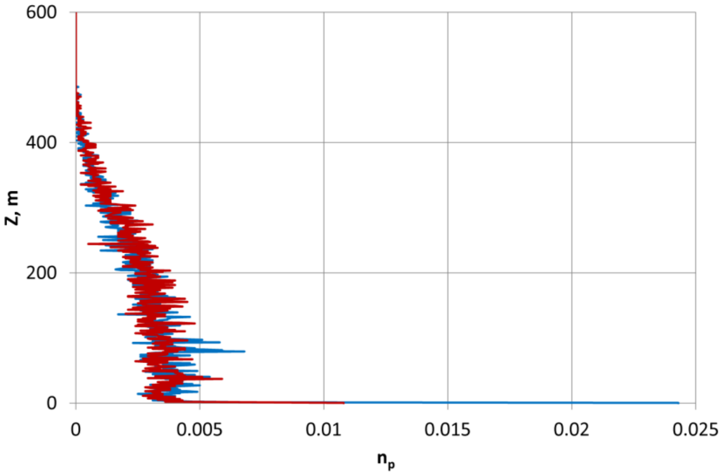
Neutral Stratification ABL test case with solid particles



Position of parcels with turbulent viscosity

Red: D_p=25 μm

Blue: D_p=50 μm



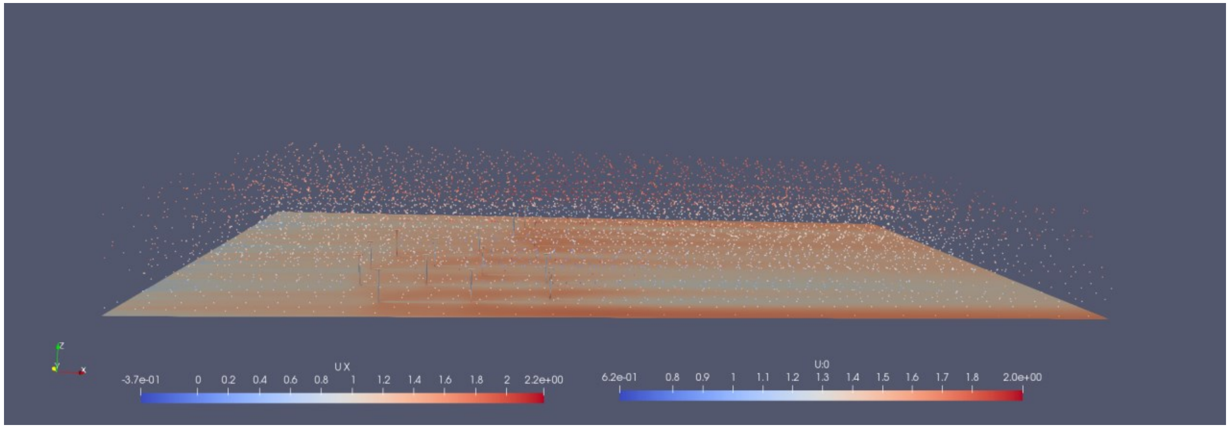
Distribution of parcels in height

M_p= 100 kg
during 1000 seconds

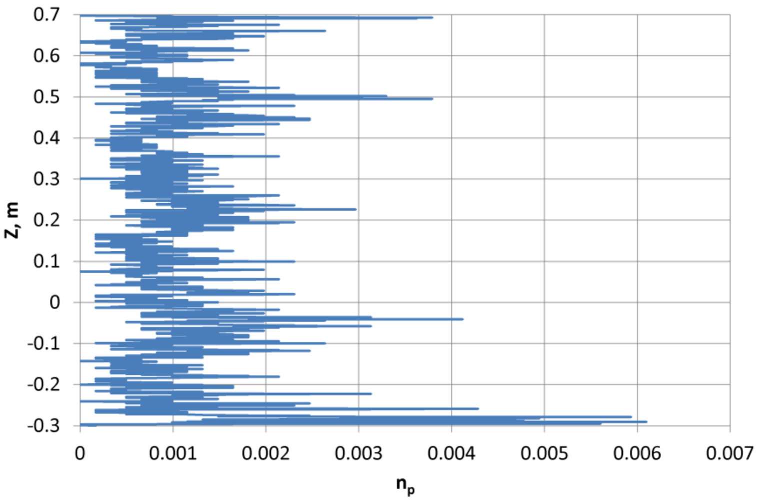
Inlet velocity of
particles:
10 parcels/s

V_{air}=8 m/s

Wind farm simulation with 14 model wind turbines with solid particles



Position of parcels in model wind farm at t=7.4 second



Distribution of parcels in height

M_p=0.0006 кг
during 10 seconds

Inlet velocity of particles:
1011 parcels/s

V_{air}= 1.5 m/s.
D_p=10^{-5} m.

Conclusion

The possibilities of the SOWFA library for solving applied problems of continuum mechanics in the field of wind energy are considered. The study of the processes of turbulent motion in the atmospheric boundary layer and in the model wind farm is proposed to be carried out using means of tracking a cloud of particles. An example of adding a particle cloud model to the ABLSolver solver and pisoTurbineFoam.ALM is given. Two new solvers have been developed for modeling the dynamics of a part in the SOWFA library. To demonstrate the work of the new solvers, the results of calculating the turbulent viscosity field for a model wind farm with 14 wind turbines are presented.

Thank you for your attention