CFD results for dust concentration in ABL near vegetative barriers

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Abstract. The numerical simulation of dust spreading inside the Atmospheric Boundary Layer are usually modelled by commercial CFD software. This contribution deals with the similar problem by using an in-house solver, based on finite volume method AUSM+up scheme. System of the RANS equations for viscous incompressible flow with variable potential temperature is used for description of the flows. The Richards-Hoxey [7] wall function is implemented to correctly caption the turbulence near the ground. The effects of vegetative barriers for the dust concentration near a surface coal mine were studied. Petroff’s [6] model of the dust deposition on vegetation is employed. The model includes four main processes which lead particles to depose on the leaves: Brownian diffusion, interception, impaction and gravitational settling.

1. Introduction

A vegetation barrier which is planned to be planted near a surface coal mine is considered. The impact of its capability to reduced dust concentration produced by a coal mine is studied.

The pollution produced by industry has negative effect on human health in surrounding inhabited areas, see e.g. [5]. The vegetative barriers are one of the common protective items. For effective planting and usage we need to understand how they works [3]. The efficiency of the vegetative barrier is quantified in presented paper.

The CFD simulation is common tool for studies of such problems, see [1] and [9]. Compared to the cited works advanced vegetation model is used in the simulation here. The vegetation is considered as a horizontally homogeneous block characterized by the leaf area density $L_{AD}$ vertical profile. $L_{AD}$ represents a foliage surface area per unit volume, the approach is adopted from [10].

The Fig 1 shows position of the coal mine and the village Braňany on the boarder of the mine. The mining company plans to plant protective vegetative barrier near the edge of the mine as is schematically sketched in the Fig. 2. Behaviour of three different Particulate Matter fractions (PM2.5, PM10 and PM75) are simulated for two variants of vegetation representing young and fully grown trees (i.e. 3 m and 15 m hight).

2. Mathematical model and numerical methods

Fluid flow is described by incompressible Reynolds-averaged Navier-Stokes (RANS) equations. The pressure $p$ and the potential temperature $\theta$ are split into background component in
Figure 1. (←) The aerial situation near the village around the surface coal mine with 2D cuts (presented cut is marked in red).

Figure 2. The scheme of 2D geometry (for chosen cut) with the planned vegetative barrier and main dust sources marked as ●. The horizontal coordinate along the cut is X.(↑)

Hydrostatic balance and fluctuations, \( p = p_0 + p' \) and \( \theta = \theta_0 + \theta' \). Boussinesq approximation is employed. Resulting set of equations reads

\[
\nabla \cdot \mathbf{u} = 0, \tag{1}
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} - \nabla \cdot (\nu_T \nabla \mathbf{u}) = -\nabla \left( \frac{p'}{\rho_0} \right) + \mathbf{g} + \mathbf{S}_u, \tag{2}
\]

\[
\frac{\partial \theta'}{\partial t} + \nabla \cdot (\theta' \mathbf{u}) = \nabla \left( \frac{\nu_T}{\Pr} \nabla \theta' \right), \tag{3}
\]

The turbulent Schmidt number \( \text{Sc} \) is set to 0.72.

**Turbulence** is modelled by standard \( k-\epsilon \) model completed with source terms acting inside the vegetation (\( S_k \) and \( S_\epsilon \) on the RHS). Model for these sources is described below. According to [4] turbulent model constants set: \( \alpha_k = 1.0, \alpha_\epsilon = 1.167, C_{\epsilon_1} = 1.44, C_{\epsilon_2} = 1.92 \) and \( C_\mu = 0.09 \).

The PM concentration transport is described by the equation for each non-dimensional mass fraction \( c_j \) representing a passive scalar:

\[
\frac{\partial \rho c_j}{\partial t} + \nabla \cdot (\rho c_j \mathbf{u}) - \frac{\partial (\rho c_j u_s)}{\partial y} = \nabla \cdot \left( \frac{\nu_T}{\text{Sc}} \nabla \rho c_j \right) + \rho F_{c_j} + S_{c_j}, \tag{4}
\]

where \( u_s \) representing the settling velocity is modelled according to [2]. \( F_{c_j} \) is the pollutant source term and \( S_{c_j} \) denotes the vegetative deposition term. The turbulent Schmidt number \( \text{Sc} \) is set to 0.72.

**Effects of vegetation** on the flow field act in three processes. The first one, a momentum sink inside the vegetation, is given in Eq. (2) by term \( \mathbf{S}_u \), expressed by \( \mathbf{S}_u = -C_d L_{AD} |\mathbf{u}| \mathbf{u} \), where \( C_d = 0.3 \) represents the drag coefficient [11]. The second process describe the influence of the vegetation on the turbulence. The turbulent source terms can be modelled by \( L_{AD} \) profile as written

\[
S_k = C_d L_{AD} (\beta_p |\mathbf{u}|^3 - \beta_d |\mathbf{u}|k), \quad S_\epsilon = C_{\epsilon_4} \frac{\epsilon}{k} S_k, \tag{5}
\]

where constants are chosen as \( \beta_p = 1.0, \beta_d = 5.1 \) and \( C_{\epsilon_4} = 0.9 \), according to [4].
The third process is dry particle deposition in the vegetation. In the model the deposition term \( S_{c_j} = -u_d \rho_p c_j L_{AD} \) is proportional to the \( L_{AD} \) profile and so called deposition velocity \( u_d \). This velocity respects four main processes: Brownian diffusion, interception, impaction and gravitational settling. Its value depends in general on the meteorological parameters, the particle size and the vegetation properties. In the study the model from [6] is adopted.

**Numerical methods** For the numerical simulation the artificial compressibility method (in dual time for non-stationary case) in finite volume formulation is employed. The inviscid terms are discretized using AUSM\(^+\)up scheme with Venkatakrishnan limiter. The viscous terms were discretized on diamond type mesh. The time integration is obtained by implicit BDF2 scheme. Finally the scheme is second order both in space and time, see [11] for more details.

The JFNK method is used for finding solution of the arising non-linear system. Inner linear systems are solved using GMRES solver. The ILU(3) preconditioner is utilized for improvement of all linear systems properties. Necessary evaluations of the Jacobians are done via finite differences [11] every 20 time steps.

Different test cases are used for the solver validation: the benchmark with rising thermal bubble in ABL [8] and comparison to measurements for flow over an isolated 2D hill. Vegetative model is set using flow in and around a forest canopy and flow around Hedgerow [10],[11]

3. **Settings**

Three main PM fractions modelled are noted as PM2.5, PM10 and PM75 according to the its particles diameter. Three mining roads and four conveyors belts are considered as the point sources (see the Fig. 2), the estimated sources intensities of the point sources are listed in the Tab. 1. The velocity in 10 m height is chosen to 1.7 m/s as the mean value from the most common velocity class.

| Type   | Source intensity [mg/s] |
|--------|-------------------------|
| roads  | 0.15 1.5 2.65          |
| conveyors | 0.1 2.9 5.8       |

Table 1. Intensities of point sources inside the mine for chosen PM fractions

Following boundary conditions are satisfied:

**Inlet**: The logarithmic profile \( u = \frac{u_{ref}}{\kappa} \ln \left( \frac{z}{z_0} \right) \) is prescribed on the inlet, the reference velocity sets as 1.7 m/s at height \( z_{ref} = 10 \) m. A roughness parameter \( z_0 \) equals to 0.1 m. The homogeneous Dirichlet boundary condition (b.c.) are prescribed for all other quantities and pressure is extrapolated from the domain.

**Top**: Velocity vector, concentration and potential temperature fluctuation are given according to inlet values and the pressure is extrapolated from the domain.

**Bottom**: The no-slip boundary is prescribed for velocity components and other quantities are extrapolated from the domain. No re-suspension of the particles fallen on the ground is allowed.

**Outlet**: Homogeneous Neumann b.c. is prescribed for velocity components, concentration and potential temperature fluctuation. Pressure is prescribed by the barometric formula.

Boundary conditions and wall functions for the **Turbulent quantities** are used according to [7].

4. **Results**

The results depends on the point of view, for the inhabitants of the village near the mine edge the point concentration in the height 1.5 m is in the interest, but for the mine company the integral characteristics as the integral mass flow of the dust concentration are needed.
The Fig. 3 shows the point concentration and the efficiency of the vegetative barrier for different three heights in comparison with situation with no new trees. The flow is decelerated inside the vegetation [3] and particles fall down. The process is more significant for heavier particles like PM75, where 82% of particles is deposed (for forest with 15 m height). This effect is not so strong for the lighter PM10 particles, remaining concentration is higher and therefore it is more dangerous for the inhabitants. Here the maximal reduction is 52%. Even the newly planted trees with height 3 m can reduced the PM10 point concentration by 28%. The lowest impact has the vegetation on the smallest particles but still the maximal reduction is almost 32%.

![Figure 3](dependency.png)

**Figure 3.** Dependency of concentration on the different forest heights ("0 m" symbolizes no new vegetation) for each PM diameter at point in a height 1.5 m above the ground.

Different situation occur when the mass flow through first 300 m in height is plotted as in the Fig. 4. The significant reduction stays only for the particles with larger diameter, the mass flow is reduced by 71% for fully grows trees. The PM10 mass flow from the mine is decreased by the maximally grown trees only by 26% and the mass flow for the smallest particles is almost staying the same (1% difference) with or without vegetative barrier. Due to the particle smaller size and of course weight, the lighter (smaller) particles are much easier carried by the flow which is wrapping the vegetative barrier. Therefore the PM2.5 is diffused to the higher altitudes and the mass flow is not decreasing for them while the point concentration near the ground is lower.

![Figure 4](mass_flow.png)

**Figure 4.** Total mass flow through the lowest 300 m of ABL for different PM fractions and tree height evaluated at $x = 0$ m.

The Fig. 5 demonstrate that the mass flow of PM2.5 is conserved through all the domain (behind the sources). The mass flow of PM10 plotted in dependence of X-axis shows the decrease in the area with the vegetation, the higher the trees are the lower the mass flow is.
5. Conclusions

Influence of the vegetative barrier on dustiness of the open coal mine was simulated. The effects of different tree heights in newly planted parts was modelled.

The efficiency of the barrier depends on the chosen method for evaluation. It can be studied either point concentration in given location (interesting for the inhabitants) or influence of the vegetation on the total amount of dust behind the barrier.

The point concentrations were significantly reduced for PM10 and PM75 particles, with the maximum reduction by 52% and 82% respectively. The influence on the lightest particles PM2.5 was not so strong, the maximal reduction was only 32%.

The influence of the vegetation on the total amount of dust is negligible for the PM particles with smaller diameter. For the heavier particles the efficiency strictly depends on the tree height. Barrier with the 15 m height catches 27% of PM10 and 71% of PM75 particles.

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Figure 5. Horizontal distribution of mass flow through bottom 300 m for PM2.5 and PM10