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ESTIMATE OF VEGETATION EFFICIENCY ON REDUCING DUST CONCENTRATION PRODUCED BY A SURFACE COAL MINE

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Abstract: A new vegetative barrier can help to reduce dust concentration in a surface coal mine neighbourhood. The project reports about quantification of this effect. An air flow field is computed together with the dust transport driven by it using an in-house CFD solver. The 2D cuts of a real geometry of Bílina coal mine in north Bohemia are used. The vegetation is modelled as horizontally homogeneous porous medium which slows the air flow inside. An influence on turbulence and filtering the dust particles by the deposition on the leaves is considered inside the barrier too. For the efficiency estimation of the barrier several integral and point criteria are used.

Keywords: Atmospheric boundary layer, particulate matter concentration, vegetative barrier, finite volume method

MSC: 65Z05, 86A10, 76F40

1. Introduction

The increased dust concentration has damaging effect on human health, see e.g. [5]. Therefore an impact study has to be performed before the coal mine can be extended, in order to minimalize potential thread to health of citizens from surrounding villages. One of precautions to lower the Particulate Matter (PM) concentration can be a newly planted vegetative barrier near the mine border. This particular study should quantify the efficiency of the vegetative barrier on decreasing the dust propagation.

Similarly as in studies [2] and [10] the problem was solved by CFD simulation of Atmospheric Boundary Layer (ABL), but newly the vegetation is modelled more in detail and special attention is paid on processes inside the vegetative barrier. 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

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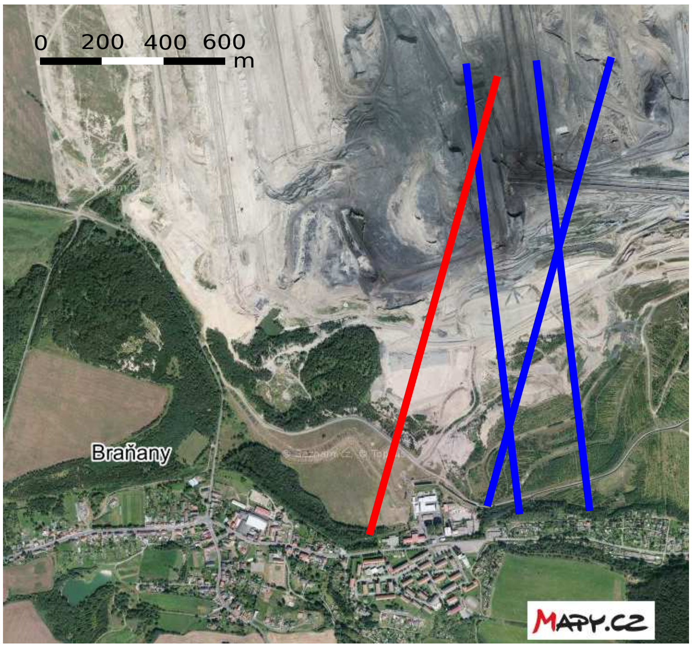

Figure 1: The situation near the village Braňany and the surface coal mine with 2D cuts (presented cut is marked)

volume, the approach is adopted from [11]. Also the advance PM deposition model based on work [6] is employed.

The situation and position of the coal mine and its neighbourhood is shown in the orthophotomap in the Fig. 1. Braňany village is situated close to the border of the mine and the present position of the mining technologies which are major sources of PM is shown in a black color inside the mine. To protect the village from the dust concentration the mining company plans to plant trees near the edge of the mine as is schematically sketched in the Fig. 2. The new vegetative barrier is simulated in two variants representing young and fully grown trees (i.e. 3 m and 15 m hight). Old vegetation outside the coal mine is also included with current height (10 m).

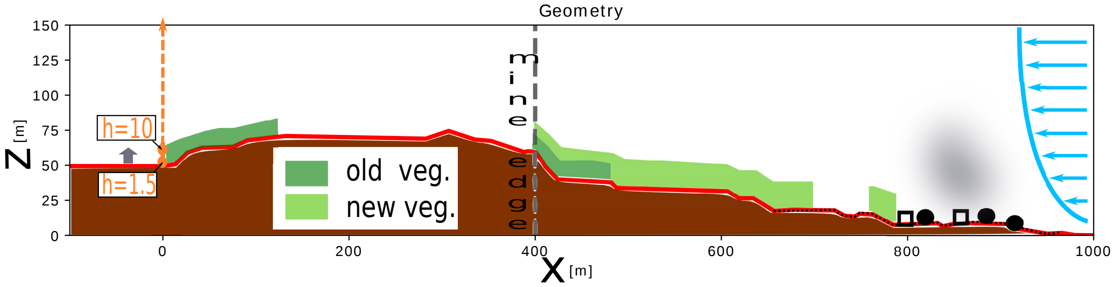

Figure 2: Scheme of the domain (for chosen cut), X is a horizontal coordinate along the cut. Main dust sources marked as ● (belt conveyors for coal) and ☐ (mine roads).

2. Mathematical model

Fluid flow is modelled by incompressible Reynolds-averaged Navier-Stokes (RANS) equations. The pressure p and The potential temperature θ are split into background component in hydrostatic balance and fluctuations, $p = p_0 + p'$ and $\theta = \theta_0 + \theta'$. Boussinesq approximation is utilized. Resulting set of equations reads

$$\nabla \cdot \boldsymbol{u} = 0, \tag{1}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} - \nabla \cdot (\nu_E \nabla \boldsymbol{u}) = -\nabla \left(\frac{p'}{\rho_0} \right) + \boldsymbol{g} + \boldsymbol{T_u}, \tag{2}$$

$$\frac{\partial \theta'}{\partial t} + \nabla \cdot (\theta' \boldsymbol{u}) = \nabla \left(\frac{\nu_E}{\mathrm{Pr}} \nabla \theta' \right), \tag{3}$$

vector $\boldsymbol{u}$ denotes averaged velocity, constant ρ_0 represents the air density at the ground level, $\nu_E = \nu_L + \nu_T$ is the effective kinematic viscosity which is a sum of the laminar and turbulent viscosity. Further $\boldsymbol{g} = (0, 0, -g\theta'/\theta_0)$ is the gravity term, $\boldsymbol{T_u}$ represent the momentum sink due to the vegetation and Pr denotes the Prandtl number equals $\mathrm{Pr} = 0.75$.

Turbulence is modelled by standard $k - \epsilon$ model completed with source terms acting inside the vegetation. Equations for turbulence kinetic energy k and dissipation ϵ (see [4]) written as

$$\frac{\partial \rho k}{\partial t} + \nabla \cdot (\rho k \boldsymbol{u}) - \nabla \cdot \left(\frac{\mu_T}{\sigma_k} \nabla k \right) = P_k - \rho \epsilon + \rho S_k, \tag{4}$$

$$\frac{\partial \rho \epsilon}{\partial t} + \nabla \cdot (\rho \epsilon \boldsymbol{u}) - \nabla \cdot \left(\frac{\mu_T}{\sigma_\epsilon} \nabla \epsilon \right) = C_{\epsilon 1} \frac{\epsilon}{k} P_k - C_{\epsilon 2} \rho \frac{\epsilon^2}{k} + \rho S_\epsilon, \tag{5}$$

are completed with a constitutive relation $\mu_T = C_\mu \rho \frac{k^2}{\epsilon}$ for the turbulent viscosity. The term P_k denotes the production of the turbulence kinetic energy, S_k and S_ϵ are sources of k and ϵ, respectively, acting inside the vegetation. Model for these sources is described below. According to [4] turbulent model constants are: $\sigma_k = 1.0$, $\sigma_\epsilon = 1.167$, $C_{\epsilon_1} = 1.44$, $C_{\epsilon_2} = 1.92$ 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:

$$\frac{\partial \rho c_j}{\partial t} + \nabla \cdot (\rho c_j \boldsymbol{u}) - \frac{\partial (\rho c_j u_s)}{\partial y} = \nabla \cdot \left(\frac{\nu_T}{\mathrm{Sc}} \nabla \rho c_j \right) + \rho F_{c_j} + S_{c_j}, \tag{6}$$

where u_s is the settling velocity modelled according to [3], F_{c_j} denotes the pollutant source term and S_{c_j} is the vegetation deposition term. The turbulent Schmidt number Sc is set to 0.72.

Effects of vegetation on the flow field act in three processes. The first one is a momentum sink inside the vegetation block given in Eq. (2) by term $\boldsymbol{T}_u$, expressed by $\boldsymbol{T}_u = -C_d L_{AD} |\boldsymbol{u}| \boldsymbol{u}$, where $C_d = 0.3$ is the drag coefficient [12]. The second process is the influence on the turbulence. The source terms in Eqs. (4) and (5) can be modelled by L_{AD} profile as written

$$S_k = C_d L_{AD}(\beta_p |\boldsymbol{u}|^3 - \beta_d |\boldsymbol{u}| k), \quad S_\epsilon = C_{\epsilon_4} \frac{\epsilon}{k} S_k, \tag{7}$$

where constants are chosen as $\beta_p = 1.0$, $\beta_d = 5.1$ and $C_{\epsilon_4} = 0.9$, according to [4].

The particle deposition in the vegetation represents the third process. According to the [6], this effect is given by the term $S_c = -L_{AD} u_d \rho_p c$ in Eq. (6). This term is proportional to the deposition velocity u_d which reflects how particles depose on the leaves. The deposition is caused by Brownian diffusion, interception, impaction and gravitational settling. The Value generally depends on the wind speed, the particle size and the vegetation properties. In this study the model from [7] is adopted.

2.1. Numerical methods

The in-house code is used. The governing equations are solved using artificial compressibility method with finite volume solver based on AUSM$^+$up scheme. The scheme is completed with the piecewise linear reconstruction supplemented by appropriate limiter. Integration in time is done by implicit BDF2 scheme. The numerical solver is described in detail in [12].

Resulting non-linear systems are solved by the JFNK method. Inner linear systems are solved using GMRES solver. The linear systems are preconditioned by ILU(3) preconditioner. Necessary evaluations of the Jacobians are done via finite differences [12].

The code has been validated on several cases: The Atmospheric Boundary Layer (ABL) flow solver was tested on the benchmark with rising thermal bubble [9] and the measurements for flow over an isolated 2D hill and the model of the vegetative barrier was validated for the flow in and around a forest canopy and flow around Hedgerow [11], [12].

3. Boundary conditions

Inlet: The logarithmic wind profile $u = u_{\text{ref}}/\kappa \ln((z - z_0)/z_0)$ is prescribed with reference velocity 1.7 m/s at height $z_{\text{ref}} = 10\,\text{m}$. A roughness parameter z_0 is set to 0.1 m. The homogeneous Dirichlet boundary condition (b.c.) are prescribed for 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** in Eq. 4 and Eq. 5 are used according to [8].

4. Settings of PM properties

The propagation of dust particles with diameter $2.5\,\mu$m, $10\,\mu$m and $75\,\mu$m and with density $1000\,\mathrm{kg/m^3}$ is simulated. The Eq. 6 is solved for each particle size separately (i.e. sectional approach). The sources positions and intensities have been obtained from the mining company and they are summarized in Tab. 1. The coal mine surface without vegetation is considered as an area dust source and it is represented as a line (in 2D). The setting of linear intensities is also listed in Tab. 1.

Type	Position [m]	Source intensity [g/s]		
		PM 2.5	PM 10	PM 75
road 1	738.3	0.00075	0.00740	0.01323
conveyor 1	744.4	0.0001	0.0029	0.0058
conveyor 2	776.6	0.0139	0.2502	0.8173
road 2	784.9	0.00015	0.00148	0.00265
conveyor 3	791.8	0.0001	0.0029	0.0058
		Source intensity [g/(m s)]		
linear sources		2×10^{-6}	1.3×10^{-5}	2.7×10^{-5}

Table 1: Position and intensities of point sources and linear intensities of uncovered areas inside the mine for chosen PM fractions

5. Computational results

During calculations it turned out that the dependency on the wind speed does not seem too significant for common velocities (0–5) m/s. Therefore only results for one velocity $u_{\mathrm{ref}} = 1.7\,\mathrm{m/s}$ are shown here.

Two types of characteristics are evaluated, point and integral. The point characteristics, e.g. concentrations in the given point, are more interesting in terms of the impact on village and their inhabitants. The integral characteristics, typically mass flows through cut, are significant in evaluation of influence of the vegetation on mine as the volume source of PM.

Firstly the point concentration of examined PM fractions at the village boarder ($x = 0\,\mathrm{m}$) is evaluated and the results are plotted in the Fig. 3. The percentages in the figures are taken from the case without newly planted vegetation (0 m). The significant reduction of the concentration is obtained for PM75, approximately by 65 % for fully grown trees. It is not surprising, the flow is decelerated inside the forest and heavy particles fall down. On the other hand, total concentration of these particles produced by the mine is low. For PM10 the total concentration is the highest and therefore they are most interesting for the inhabitants. In this

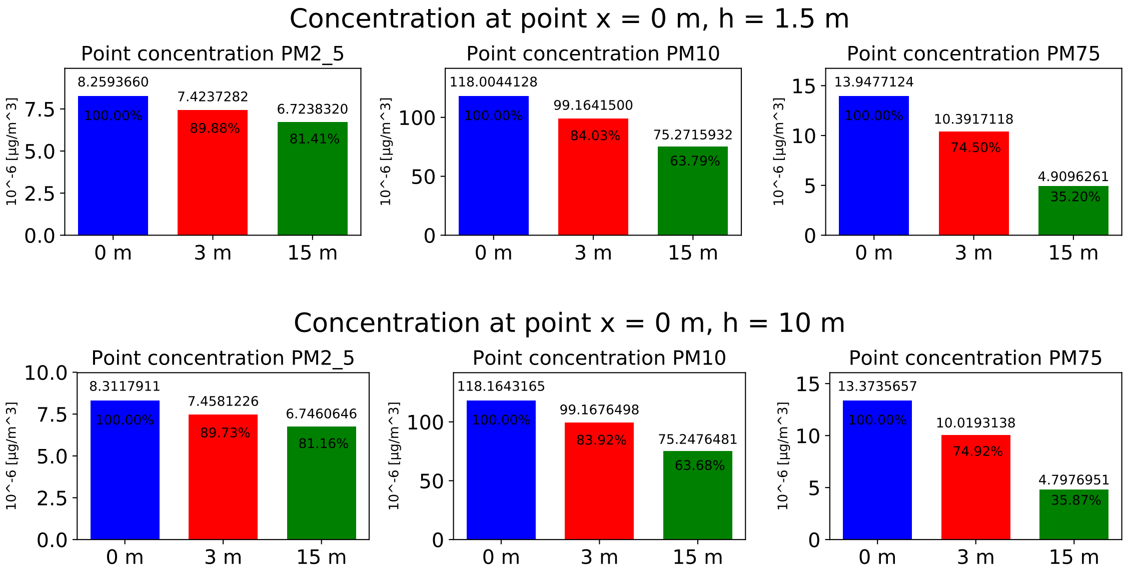

Figure 3: Concentration for each PM diameter at points 1.5 m and 10 m above the ground for different tree height ("0 m" symbolize the case without new vegetation)

case the efficiency of the barrier is 16 % for young forest and more than 36% for the fully grown one. Similar effect is visible for PM2.5 with efficiency 10 % and 18 %. The height of the point concentration evaluation has not got an important effect, if the usual building heights is considered. The difference in barrier efficiency between points concentration in 1.5 m or 10 m is in an order of per-mille for all the PM fractions.

If the total PM mass flow from the mine is requested, the results for barrier efficiency are distinctly different. The Fig. 4 clearly displays that the efficiency of fully grown trees (15 m) is only 1.5 % for PM2.5. The improvement for PM10 is only 7 % in case of 3 m trees and around 20 % in the case of 15 m trees, for PM75 the improvement remains significant around 45 % for 15 m trees. The efficiency of the

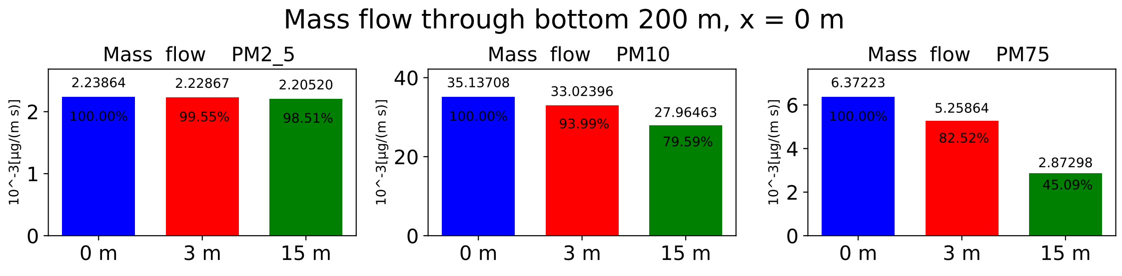

Figure 4: Integral mass flow through the first 200 m of air column for different PM fractions and different tree height (at $x = 0\,\mathrm{m}$)

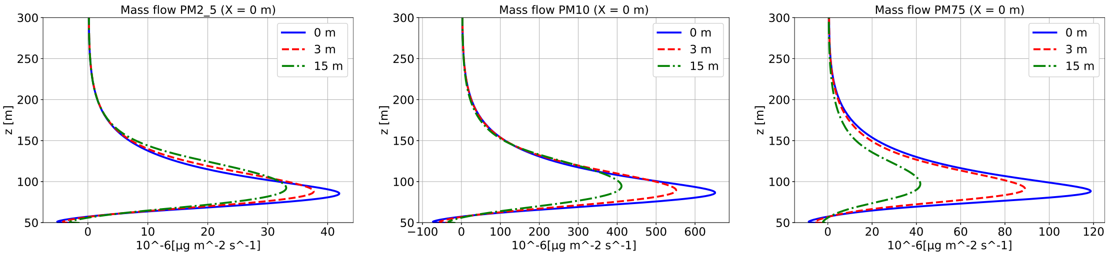

Figure 5: Mass flows for different PM fractions in vertical cut $x = 0\,\mathrm{m}$

barrier reduction of the source intensity is for the lighter particles negligible. It is given by the different behaviour of the particles which is clearly demonstrated in the Fig. 5 where the vertical profiles of the mass flow are shown. Most of lighter particles do not enter the forest due to deflection of the flow and increase of the turbulence by vegetation. This effect leads to the spreading of pollutant to the higher parts of the atmosphere, see [1]. Maxima of the mass flow are reduced in all cases, but their position is shifted up for smaller particles (PM2.5).

Different point of view is represented by Fig. 6, where the horizontal distribution of the vertical mass flow is shown. Significant dependency on the forest height is clearly visible for the PM10 and the PM75. It is particularly important to notice significant decrease of the number of particles in the forest. The PM2.5 particles aren't significantly reduces by the trees of any height.

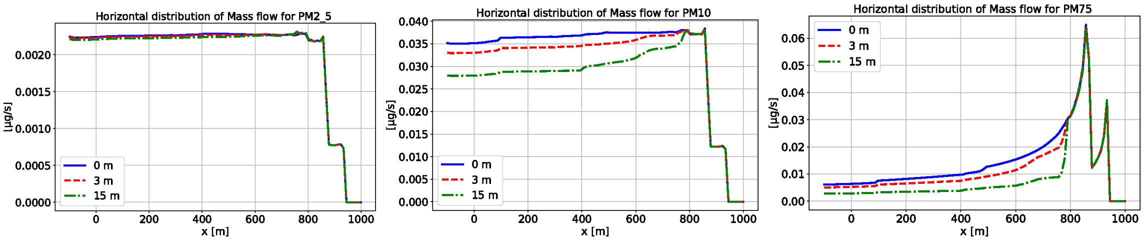

Figure 6: Horizontal distribution of vertical mass flows for different PM fractions

6. Conclusions

Effects of the vegetative barrier height and particle diameter on the dust concentration emitted from the coal mine in the case of real topography were studied. Near ground concentrations of all PM fractions are significantly reduced with vegetation, but the vegetative barrier is more effective for the heavier particles (PM10, PM75). The concentration of the most produced particles PM10 is lowered in the best case (fully grown trees) by 36 %. Influence of the vegetation on mine as a volume dust source is noticeable only for the particles with larger diameter. It is necessary to say, the results are very sensitive to exact capture of the fluid flow and parametrisation of the vegetation plays significant role.

Acknowledgements

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