Modelling of the Influence of Vegetative Barrier on Concentration of PM10 from Highway

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Abstract. The influence of different types of the vegetative barrier near a highway on dustiness was studied. Transport and dispersion of pollutants PM10 emitted from the highway were numerically simulated. Mathematical model was based on the Navier-Stokes equations for turbulent fluid flow in Boussinesq approximation. The AUSM-MUSCL scheme in finite volume formulation on structured orthogonal grid was used.

1. Introduction
The pollution in the Atmospheric Boundary Layer (ABL) is increasing these days. The numerical modelling can help us to predict the transmission of the pollution and to understand its behavior ([1] and [2]). The core of this problem lies in an accurate fluid flow modelling.

The increasing car traffic on highways is one of the major problems. The concentration of pollution produced (or swirled) by the traffic is increasing as well. Therefore areas around the highways become contaminated and dangerous for human activity. Instalation of the various types of obstacles is the most widely used method for solving of this problem. Influence of the vegetative barrier near the highway on the dustiness was numerically studied in this paper. Effect of the selected parameters, especially shape and type of vegetation on the concentration of PM10 was investigated.

2. Mathematical model
The air flow in ABL is described by the 2D system of RANS (Reynolds Averaged Navier-Stokes) equations for the viscous, incompressible, turbulent and stratified flow with variable density (in general), simplified by the Boussinesq approximation.

\[
\begin{align*}
\frac{\partial u_j}{\partial x_j} &= 0, \\
\frac{\partial \rho}{\partial t} + \frac{\partial u_j \rho}{\partial x_j} &= u_2 \frac{\partial \rho_0}{\partial x_2}, \\
\frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} + \frac{1}{\rho_0} \frac{\partial p}{\partial x_i} &= \frac{\partial}{\partial x_j} \nu \left( \frac{\partial u_i}{\partial x_j} \right) - \frac{\rho}{\rho_0} g \delta_{i2} + T_i, \\
\frac{\partial \rho C}{\partial t} + \frac{\partial (\rho u_j C)}{\partial x_j} &= \frac{\partial}{\partial x_j} D \left( \frac{\partial C}{\partial x_j} \right) + Z
\end{align*}
\]
where \( u_i \ (i \in \{1, 2\}) \) are velocity components, \( \rho \) resp. \( p \) are density and pressure perturbations, \( C \) is pollution concentration, \( \rho_0 \) is the background density field and \( T_i \) is the aerodynamic resistance of the barrier, \( Z \) is source term placed on the highway. The modelled PM10 particles are assumed as a non-hygrosopic, primary emitted contaminant which can be considered as passive scalar in the flow field.

The viscosity was composed from the molecular kinematic viscosity and the turbulent viscosity \( \nu = \nu_m + \nu_T \). The turbulent viscosity is computed according to [5], [4] from

\[
\nu_T = l^2 \left| \frac{\partial u_1}{\partial x_2} \right|, \quad l = \frac{\kappa(x_2 + z_0)}{1 + \kappa(x_2 + z_0)/l_{\infty}}, \quad l_{\infty} = \frac{27 |V_g| 10^{-5}}{f},
\]

where \( \kappa \) is von Karman constant, \( f \) marks Coriolis parameter \( f = 1.1 \cdot 10^{-4} \text{ rad.s}^{-1} \), \( z_0 \) is surface roughness parameter (choose as tenth of barrier height \( h \)), \( l_{\infty} \) means mixing length for \( x_2 \to \infty \) and \( V_g \) is geostrophic velocity on the top of boundary domain.

### 2.1. Vegetation model

The vegetative barrier is modelled by the volume force \( T \) in momentum equations, which simulates the aerodynamic resistance caused by the vegetation

\[
T_i = r_h |U| u_i, \quad r_h(z) = \begin{cases} 
    r \frac{x_2/h}{0.75} & \forall(x_2/h); \quad 0 \leq x_2/h \leq 0.75 \\
    r \frac{1-x_2/h}{1-0.75} & \forall(x_2/h); \quad 0.75 \leq x_2/h \leq 1.0,
\end{cases}
\]

here \( |U| \) is the velocity magnitude and \( r_h \) is an obstructing coefficient of the vegetative barrier. The vertical profile of this parameter has been set–up as rhombus which simulate the distribution of the tree mass and its ability to obstruct the flow where \( r \in (0;1) \). Different values of these constants have been tested.

### 3. Numerical approximation

The AUSM scheme in finite volume formulation is used for space discretization of the inviscid fluxes. Velocities on the cell faces are computed using MUSCL reconstruction according to van Leer [6] with Hemker-Koren limiter. Since the pressure is approximated by the central way, the scheme has to be stabilized by the artificial pressure diffusion introduced in [7]. The viscous fluxes are discretized in the central way on dual (diamond type) mesh. This scheme is of the second order in space. For details see [3], [8]. After the space discretization the time derivative is approximated by the robust second order BDF formula. The time step \( \Delta t \) can be chosen according to the problem. The artificial compressibility method in an artificial (dual) time is used. The resulting system of ODEs is solved by an explicit 3-stage Runge-Kutta method.

The validation of the model was done on case study solved by Bodnar [5], for more information see [9].

### 4. The numerical experiment and setup

The computational domain was \( 300 \times 150 \) m large, the highway is situated in position \( x_1 \in \langle 20, 45 \rangle \) m. The vegetative barrier of height \( h = 15 \) m is located in position \( x_1 \in \langle 50, 80 \rangle \) m. Dust source was situated to the center of the highway \( x_1 = 32 \) m. The source term was set to \( Z/\rho_0 = 1 \) for all time. Some other parameters are \( g = -10 \frac{m}{s^2} \), kinematic viscosity of air \( \nu = 10^{-5} \frac{m^2}{s} \), \( \frac{\partial \rho_0}{\partial z} = 0 \).

The structured Cartesian grid of \( 120 \times 300 \) cells is equidistantly spaced in \( x_1 \)-direction. The vertical step till height 50 m is exponentially diluted, above 50 m is equidistant with 2 m step. The smallest step is 0.1464334293 m high in \( x_2 \)-direction (designates in experiments for clarity \( y \)-direction).
5. Results

The influence of the obstructing constant on the flow field and concentration was studied. Five different cases for \( r = 0, 0.2, 0.4, 0.8, 1.0 \) has been considered. The typical plot of \( u_1 \) velocity and PM10 concentration are shown in Figs. 1 and 2.

Dependance of the horizontal velocity component on parameter \( r \) in \( y=10 \) m is plotted in Fig. 3. The red line shows the situation, when \( r = 0.0 \) (without barrier). No breaking effect appeared for this line. However the velocity at the same high is decreasing. The explanation can be in boundary layer evolution, turbulent viscosity draw kinetic energy. The rapid acceleration of the flow for other \( r \) away from the barrier (behind \( x = 90 \) m) is caused probably by the faster stream of fluid close to the ground. These levels were not breaking so well, because the drag coefficient is lower here (see Eq. (3)).

The vertical distribution of concentration in point \( x = 150 \) m for different \( r \) is plotted in Fig. 4 and summarized in Tab. 1. The maxima of concentrations are decreasing with increasing of density of vegetation. The large part of the PM10 is transported in higher part of ABL due to flow field deformation caused by the vegetative barrier. So the maxima are shifted to the higher levels.

This tendency illustrate Fig. 6 where the distribution of concentration on parameter \( r \) in two heights (\( y = 2 \) m and \( y = 10 \) m) is shown. The concentration in 2 m level decrease more then 5 times till \( r = 0.4 \) and then remains approximately the same. On the other hand, concentration in 10m level uniformly increase.
Table 1. Values of concentrations for position $x = 150$ m depending on $r$ and height $y$

|       | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.8 | 1.0 |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| $y=2$ m | 0.40 | 0.54 | 0.34 | 0.12 | 0.06 | 0.04 | 0.03 | 0.02 |
| $y=10$ m | 0.00 | 0.01 | 0.02 | 0.04 | 0.07 | 0.09 | 0.18 | 0.20 |

Figure 5. Horizontal distribution of the concentration for different $r$ in $y = 10$ m

Figure 6. Dependence of the PM10 concentration on obstructing coefficient.

6. Conclusions
The numerical scheme for ABL flows with passive concentration has been developed and they has been used successfully for simulation of the flow over vegetative barrier. Several numerical results for different obstructing coefficient was obtained. The influence of the barrier density on the PM10 concentration was demonstrated.

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