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Numerical Simulation of Wind Flow in the Vicinity of Forest Block

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Summary

This paper presents some of the results of numerical simulation of flow in the proximity of forest block. The mathematical model is based on Reynolds averaged Navier-Stokes equations for incompressible flows. The forest canopy model introduces some additional aerodynamic forces into these equations. Turbulent closure of the model is obtained by simple algebraic turbulence model. The numerical solution is carried out by the semi-implicit finite-difference scheme. The results of simple tests are presented and summarized. Model sensitivity has been studied with respect to canopy parameters.

Introduction

This study has been motivated by the request of one coal mining company to evaluate the possible effect of vegetation on the deposition of wind drifted coal dust. In the presented part of this project we have concentrated our attention to the detailed computation of flow field characterictics in the vicinity of vegetation blocks. Special attempt has been made to localize the places where the flow is decelerating, descending or recirculating. These flow regimes areas could be critical from the point of view of surface particle deposition.

Because of the future application of the developed model it was necessary to test it on some specific terrain orography profiles. The case we are interested in is characterized by the presence of forest block in the proximity of coal mine edge. The joint effect of complex topography and vegetation influence has been studied.

Mathematical Model

The flow in atmospheric boundary is turbulent in most simulations. The fluid motion can be thus described by the Reynolds averaged Navier-Stokes equations (RANS). The non-conservative form of the RANS system is represented by the following equations:

$$u_x + v_y + w_z = 0 \tag{1}$$

$$V_t + uV_x + vV_y + wV_z = -\frac{\nabla p}{\rho} + [KV_x]_x + [KV_y]_y + [KV_z]_z + \vec{f}_V \tag{2}$$

Here $V = col(u,v,w)$ is the velocity vector, p is pressure, ρ is density. The force vector $\vec{f}_V$ includes the specific aerodynamic force corresponding to the drag induced by the vegetation. See [1] and [2] for details.

$$\vec{f}_V = col(-c_d a|V|u, -c_d a|V|v, -c_d a|V|w) \tag{3}$$

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In the above expression the $c_d(z)$ denotes the bulk drag coefficient of trees (as a function of vertical coordinate z). The characteristic area of canopy $a(z)$ could be evaluated as a product of leaf area density $a^*[m^2 \cdot m^{-3}]$ and the local canopy height $h[m]$, i.e. $a(z) = a^* h$. In or work we deal with total resistance parameter $r_h(z) = c_d a$. The vertical profile of this parameter has been set-up in the following way:

$$r_h(z) = \begin{cases} r\,\frac{z/h}{0.75} & \text{for} \quad 0 \le z/h \le 0.75 \\ r\,\frac{1-z/h}{1-0.75} & \text{for} \quad 0.75 \le z/h \le 1.0 \end{cases} \tag{4}$$

The turbulence model is based on the Boussinesq hypothesis on the turbulent diffusion coefficient $K = \nu + \nu_T$ which is expressed as a sum of molecular and eddy viscosity. Finally the following algebraic turbulence model was used to complete the governing system:

$$K = \nu + \nu_T \qquad \text{where} \qquad \nu_T = \ell^2 \left[\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right]^{1/2} \tag{5}$$

The mixing length ℓ is computed according to the following formula:

$$\ell = \frac{\varkappa (z + z_0)}{1 + \varkappa \frac{(z+z_0)}{\ell_\infty}} \qquad \text{where} \qquad \ell_\infty = \frac{27\,|V_G|\,10^{-5}}{f_c} \tag{6}$$

Here $f_c = 1.1 \cdot 10^{-4} ms$ denotes the Coriolis parameter and V_G is the geostrophic wind velocity at the upper boundary of domain.

Numerical Solution

According to our previous experience with computation of atmospheric boundary layer flows, we have used semi-implicit finite difference scheme to resolve numerically the above mentioned governing system. See [3] and [4] for details. The mesh used in our simulations is structured, non-orthogonal, wall fitted with 1000×40 cells. The dimensions of computational domain are $1000 \times 300 m$. The inlet velocity profile follows up to the height $200 m$ the power-law with exponent $2/9$. Above this height the velocity is kept constant. The typical forest block has width $90 m$ in our simulations. The different values of forest canopy resistance r and height h were used.

Numerical Results

Because of the lack of the space, just few results could be presented here. The first case we have solved was the flow over the flat terrain without and with the forest block. This basic case should give us some idea about the influence of vegetation on the overgoing flow. The inlet undisturbed velocity profile has the maximum speed 10 m/s. The assumed velocity profile had been governed by a power-law with exponent $2/9$. The uniform surface roughness has been assumed with $z_0 = 0.2m$.

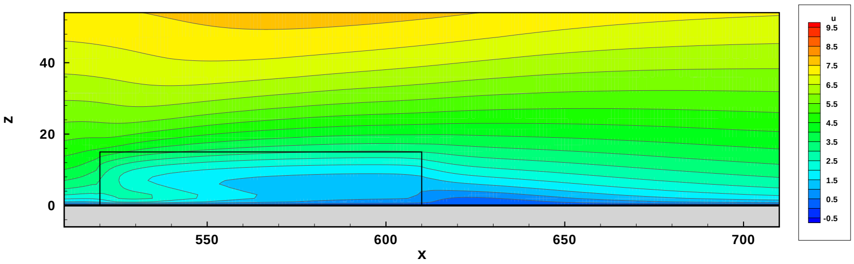

Figure 1: Isolines of horizontal velocity component in the proximity of forest block situated in flat terrain.

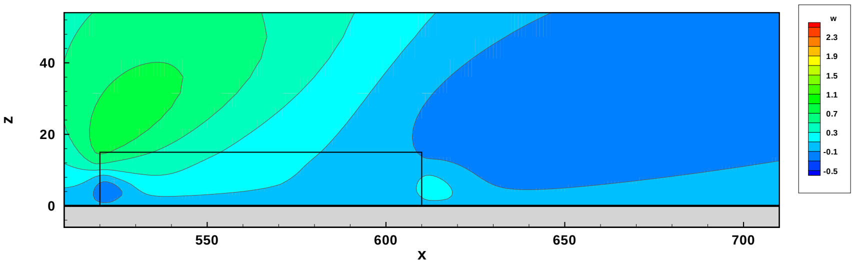

Figure 2: Isolines of vertical velocity component in the proximity of forest block situated in flat terrain.

The region of descending flow is indicated in the following figure, where the contours of negative part of vertical velocity are drawn.

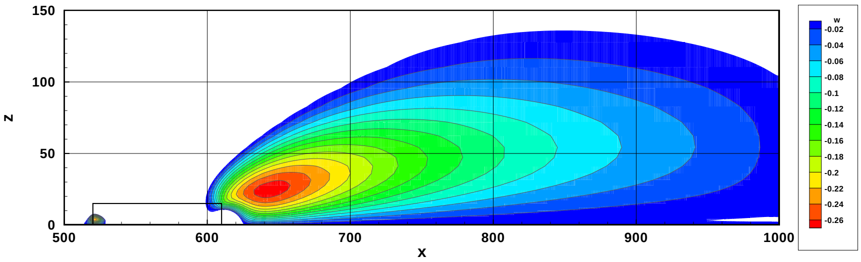

Figure 3: Isolines of negative part of the vertical velocity component in the proximity of forest block situated in flat terrain.

The near-ground longitudinal velocity profiles are drawn in the following figures 4 and 5. The undisturbed profiles are drawn by dashed line, while the velocity profile in the presence of forest block is drawn by solid line. The region where the the vegetation is placed is shaded in both figures.

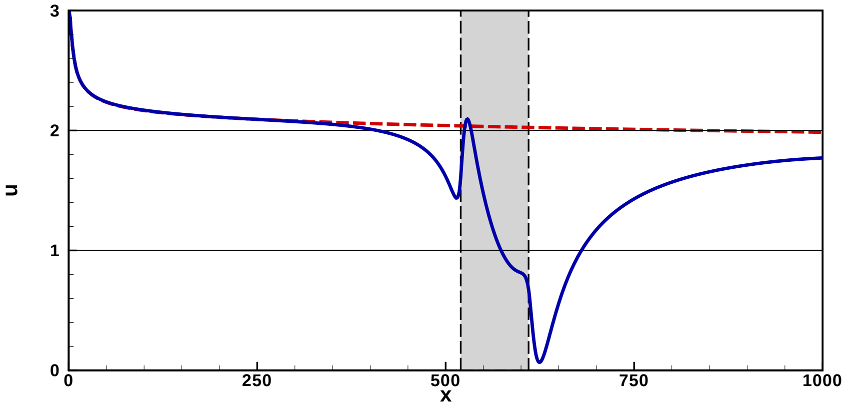

Figure 4: Longitudinal profile of the near-ground horizontal velocity component *u* in flat terrain. (- - - without forest, —— with forest).

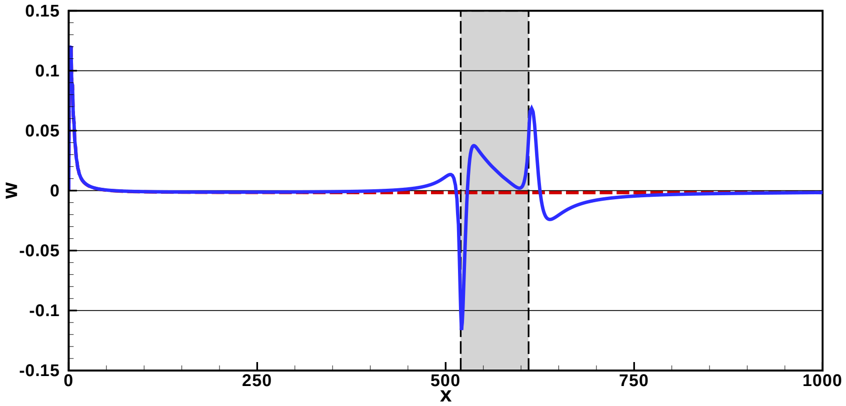

Figure 5: Longitudinal profile of the near-ground vertical velocity component *w* in flat terrain. (- - - without forest, —— with forest).

In the above figures 4 and 5 we can clearly identify the deceleration of the flow inside the forest block, so as in the zone just behind the forest.

Complex terrain profile chosen for the following simulations is based on the real terrain profile in the proximity of coal mine edge. It is characterized by a large step in orography profile. The forest block, the influence of which is explored here, is place close to this orography step. The shape of the computational domain is apparent from the following figure 6, where the isolines of horizontal velocity component are drawn.

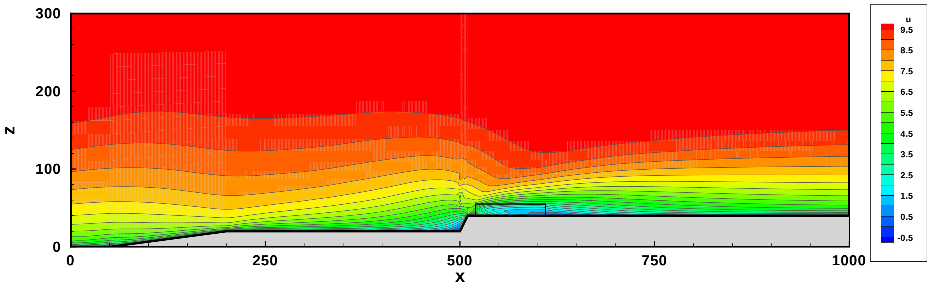

Figure 6: Isolines of horizontal velocity component in complex terrain with forest block in proximity of orography step.

The sensitivity of the presented model on the aerodynamic resistance parameter r has been explored in detail for the above geometry. In this case the height of the forest block was assumed to be constant $h = 10m$. The results summary of this tests is shown in the following figure:

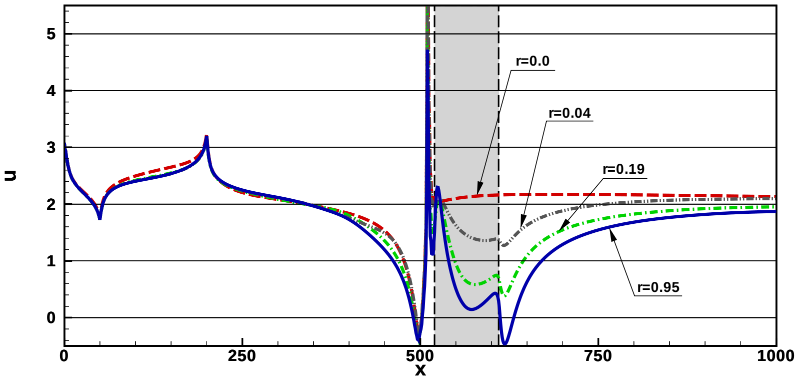

Figure 7: Longitudinal profile of the near-ground horizontal velocity component for different values of resistance r. $(r = 0.0; 0.04; 0.19; 0.95)$

There is visible deceleration of the flow inside and behind the forest block, where the flow recirculation appears behind the forest for high value of resistance parameter. The other parameter appearing in the forest canopy parametrization is the canopy height h. The dependency of the near-ground horizontal velocity on this height is shown in the following figure.

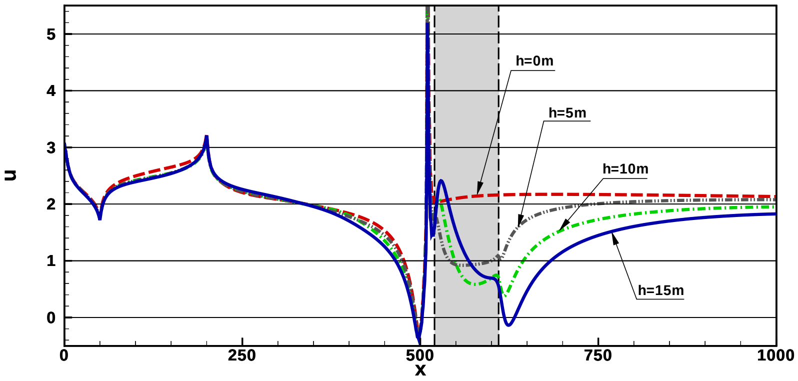

Figure 8: Longitudinal profile of the near-ground horizontal velocity component for different values of canopy height h. ($h = 0; 5; 10; 15m$)

Conclusions & Comments

- The model has proved its applicability to the complex terrain simulations.
- The results obtained using this model are in good qualitative agreement with our expectations for the solved cases.
- Turbulence model used within the presented model needs to be modified to get closer agreement with observations.
- The effects of the forest blocks should be further explored in three-dimensional case.

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