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NUMERICAL OPTIMIZATION OF NEAR-ROAD VEGETATION BARRIERS

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Abstract. *The contribution deals with the numerical simulation of the influence of near-road vegetation barriers on the dustiness along the highway. Vegetation barrier close to the road has been proposed to reduce the amount of PM10 and PM75 in nearby areas.*

The flow in the Atmospheric Boundary Layer (ABL) is assumed to be incompressible, yet the density is not constant due to the gravity. The flow is described by the RANS equation for viscous incompressible flow with variable density. The two equations turbulence model is used for the closure of this set of equations. Three effects of the vegetation should be considered: effect on the air flow, i.e. slowdown or deflection of the flow, influence on the turbulence levels inside and near the vegetation, and filtering of the particles present in the flow. Deposition velocity reflects four main processes by which particles depose on the leaves: Brownian diffusion, interception, impaction and gravitational settling.

The numerical scheme is based on the finite volume method and artificial compressibility method. For the convective terms the AUSM+up scheme is used. Second order accuracy is achieved via the linear reconstruction, where gradients are calculated using least squares approach. For the viscous fluxes diamond type scheme is used. Resulting set of ODE equations is integrated using BDF2 method.

49 variants of the vegetation differ in the density, width and height were simulated. The influence of the mentioned parameters were examinated. Main processes affecting the dustiness in modeled cases are emphasized.

1 Introduction

Increasing level of dustiness is one of the major problems mainly in the populated areas. The atmospheric particulate matter (PM) has a significant negative impact on the human health, as was demonstrated in the numerous studies. Apart from industry and local heating, vehicular traffic is one of the major sources of particulates. Near road vegetation barriers were proposed as a means of the reduction of a harmful PM in the atmosphere. Their effectivity is influenced by a number of parameters: atmospheric conditions, properties of the particulates, vegetation type or its position. Experimental studies of this flow both on-site and in wind tunnels are complicated and expensive. One of the appropriate ways how to understand the phenomena of vegetation flows and particle transport are the numerical simulations.

The effect of the vegetation on the air flow alone has been subject of the research for a long time. Although number of studies dealing with near-road flow field, vegetation and pollutant dispersion have been published, research on deposition of the particulate matter on the vegetation is still ongoing. Computationally efficient RANS models of horizontally homogeneous canopy are often used in studies of vegetation barriers [1]. To capture detailed temporal evolution of the flow field, LES models of horizontally homogeneous canopy were also used [2]. Advances in high-performance computing allowed to simulate complex models of detailed 3D canopy architecture resolved to the level of stems and branches [3]. Problems connected with the modeling of the stratified fluid are solved in [4, 5].

Several reviews on related topics are available, dealing with dry deposition on canopies [15] or focusing on a relation between air pollution and vegetation in an urban setting [13, 10]. Among modeling studies on particle dispersion through vegetation barrier are those investigating in 2D and 3D computational domains [17, 22, 19]. Problem of dust transport in real-world situations has been numerically investigated in [7, 8].

In this paper we investigate influence of the vegetation block over the highway notch. Aim of this study is to determine effects of the near-road barrier under varying vegetation parameters, namely width and height of the block and its density. We use simplified 2D model of a horizontally homogeneous vegetation block with original LAD profile. Main objective is to investigate influence of the barrier on pollutant concentration behind the barrier.

2 Numerical model

2.1 Physical and mathematical model

We are interested in the modeling of the flow in the lowest part of ABL, approximately 200 meters over the ground. Velocities here vary in the order of ones or tenth m/s, the flow can be modeled as incompressible, but due to the gravity force the density isn't constant, the fluid is stratified. The second significant problem is the presence and modeling of the vegetation (forest or bushes), which has a major influence on the air flow. Three effects of its should be considered: effect on the air flow, i.e. slowdown or deflection of the flow, influence on the turbulence levels inside and near the vegetation, and the filtering of the particles present in the flow.

2.1.1 Equations for the fluid motion

This type of flow can be described by the Reynolds-averaged Navier-Stokes (RANS) for viscous, incompressible, stratified fluid. These equations are rewritten using Boussinesque hypothesis. The pressure p and potential temperature θ are split into background component in hydrostatic balance and fluctuations, $p = p_0 + p'$ and $\theta = \theta_0 + \theta'$. Boussinesq approximation stating that changes in density are negligible everywhere except in the gravity term is utilized. Resulting set of equations is written here

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

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} + \nabla(p'/\rho_{\text{ground}}) = \nu_E \nabla^2 \boldsymbol{u} + \boldsymbol{g} + \boldsymbol{S_u}, \tag{2}$$

$$\frac{\partial \theta}{\partial t} + \nabla \cdot (\theta \boldsymbol{u}) = \frac{\nu_E}{\text{Pr}} \left(\nabla \cdot (\nabla \theta)\right). \tag{3}$$

Vector $\boldsymbol{u}$ stands for velocity, ρ_{ground} is the air density ρ at the ground level, $\nu_E = \nu_L + \nu_T$ is the sum of the laminar and turbulent kinematic viscosity, $\boldsymbol{g} = (0, g\frac{\theta'}{\theta_0}, 0)$ is the gravity term, $\boldsymbol{S_u}$ represent the momentum sink due to the vegetation and Pr $= 0.75$ is the Prandtl number.

2.1.2 Turbulence

For the closure of previous equations, standard $k - \epsilon$ model is used. Equations for turbulence kinetic energy k and dissipation ϵ are as follows:

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

$$\frac{\partial \rho \epsilon}{\partial t} + \nabla \cdot (\rho \epsilon \boldsymbol{u}) = \nabla \cdot \left(\left(\mu_L + \frac{\mu_T}{\sigma_\epsilon} \right) \nabla \epsilon \right) + C_{\epsilon_1} \frac{\epsilon}{k} P_k - C_{\epsilon_2} \rho \frac{\epsilon^2}{k} + \rho S_\epsilon. \tag{5}$$

The model is completed by a relation between k, ϵ and the turbulent dynamic viscosity μ_T, $\mu_T = C_\mu \rho \frac{k^2}{\epsilon}$. In the equations above μ_L is the laminar dynamic viscosity, P_k is the production of the turbulence kinetic energy, and S_k and S_ϵ are sources of k and ϵ respectively. Both could be written as the sum of a road traffic part and a part due to the vegetation, $S_k = S_k^r + S_k^v$, $S_\epsilon = S_\epsilon^r + S_\epsilon^v$. Sources due to the road traffic are modeled by the model from [6]. Sinks and sources caused to the vegetation are described in the next section.

Following constants of the model are used: $\sigma_k = 1.0$, $\sigma_\epsilon = 1.167$, $C_{\epsilon_1} = 1.44$, $C_{\epsilon_2} = 1.92$ and $C_\mu = 0.09$.

2.1.3 Particle transport

Pollution dispersion is calculated using transport equation for non dimensional mass fraction w,

$$\frac{\partial \rho w}{\partial t} + \nabla \cdot (\rho w \boldsymbol{u}) - (\rho w u_s)_y = \nabla \cdot \left(\frac{\nu_E}{\text{Sc}} \nabla \rho w \right) + \rho f_c + S_w. \tag{6}$$

Here f_c is the source term and S_w is the vegetation deposition term. Based on the review and the discussion in [23], the Schmidt number Sc $= 0.72$ was used. The settling velocity u_s of a spherical particle with the diameter d and density ρ_p is given by the Stokes' equation, $u_s = (d^2 \rho_p g C_c)/(18\mu)$, with the correction factor $C_c = 1 + \frac{\lambda}{d}\left(2.34 + 1.05 \exp(-0.39 d/\lambda)\right)$, where $\lambda = 0.066$ µm is the mean free path of the particle in the air [9].

2.1.4 Vegetation

Vegetation model plays an important role. We suppose vegetation as horizontally homogenous, its properties are described by vertical *Leaf area density* (LAD) profile - foliage surface area per unit volume - and a leaf type and size. We have used original LAD profile shown in Figure 1. This basic LAD profile is multiplied by the coefficient representing the density of vegetation.

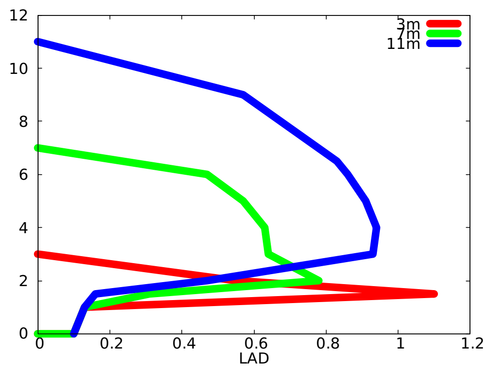

Figure 1: LAD profile

The effects of the vegetation can be divided into three parts: first, it is drag induced by the vegetation and this caused sink in the momentum equation, (2)

$$\boldsymbol{S}_u = -C_d \mathrm{LAD} |\boldsymbol{u}| \boldsymbol{u}$$

Here $C_d = 0.3$ is the drag coefficient [11].

Secondly, it is the influence on the turbulence levels. Following [11], we model this term as

$$S_k^v = C_d \mathrm{LAD}(\beta_p |\boldsymbol{u}|^3 - \beta_d |\boldsymbol{u}| k), \quad S_\epsilon^v = C_{\epsilon 4} \frac{\epsilon}{k} S_k^v,$$

in Eqs. (4) and (5) with constants $\beta_p = 1.0$, $\beta_d = 5.1$ and $C_{\epsilon_4} = 0.9$.

And lastly, it is a particle sink term in Eq. (6), $S_w = -\mathrm{LAD} u_d \rho w$. The term is proportional to the deposition velocity u_d. Deposition velocity reflects four main processes by which particles depose on the leaves: Brownian diffusion, interception, impaction and gravitational settling. Its value generally depends on wind speed, particle size and vegetation properties. In this study, the model from [16] derived for broadleaf trees was used.

2.2 Numerical method

For the numerical solution the finite volume method in connection with artificial compressibility method were used. The continuity equation (1) is rewritten in the next form,

$$\frac{1}{\beta} \frac{\partial p'}{\partial t} + \nabla \cdot \boldsymbol{u} = 0. \tag{7}$$

The choice of the parameter β is discussed e.g. in [14], here we have used $\beta = 1000$.

Transformed set of equations is discretized using the finite volume method on unstructured grid. For the convective terms the AUSM+up scheme [12], designed for all speed flows, is used. Second order accuracy is achieved via the linear reconstruction, where gradients are calculated using least squares approach. To prevent artificial overshooting, Venkatakrishan limiter [24] is utilized. For discretization of viscous terms a dual mesh is used (diamond type scheme).

The resulting set of ordinary differential equations is solved using an implicit BDF2 method of the second order. In every time step, first the system of the Navier-Stokes equations (2, 3, 7) is solved, followed by the system of the $k - \epsilon$ equations (4, 5) and then by the system of the passive scalar equations (6). Values of turbulent viscosity, coupling together turbulence equations with the Navier-Stokes equations, are taken from the previous time step.

Each of these nonlinear systems is solved by the Newton method. Inner linear systems are solved using matrix-free GMRES solver. The linear systems are preconditioned by ILU(3) preconditioner. To construct the preconditioner matrices, Jacobian of the system is needed. Its evaluation via finite differences is a costly operation, which we reduce by two complementing approaches: via matrix coloring, which exploit the sparseness of the Jacobian, and by calculating the preconditioner matrices (as well as the Jacobians) only every 20 iterations.

3 Numerical results

Large number of parameters play role in model presented above. Sensitivity analysis were performed in our previous studies [20], [21], where the influence of various types of meteorological conditions and geometrical configurations were tested. Based on this computations, following test case was chosen as a representative.

3.1 Case settings

The computational domain is $350\ m$ long ($x \in< -50, 300 > m$) and $100\ m$ high and represents highway notch. Schematic sketch of the domain is shown in Figure 2. Road is situated between $20\ m$ and $45\ m$, side slopes in the angle $45°$ are $4\ m$ heigh and are placed on both sides of the highway in $x \in< 16, 20 > m$ and $x \in< 50, 54 > m$. Four sources of pollutant, representing the road, are placed between 23 m and 42 m from the inlet at the height of 0.8 m. Vegetation block is placed downstream from the road above the notch and starts in $x = 55$m.

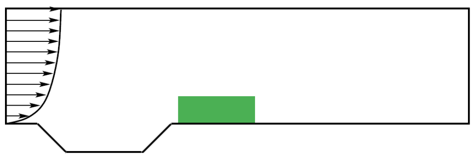

Figure 2: Sketch of the domain (not to scale)

We model the particles of diameter 10 µm and 75 µm with density 1000 kg/m^3. Each source of the pollutant has the intensity 1 µg/s. No resuspension of the particles fallen on the ground is allowed. Density of the traffic is set to 16 passenger cars and 4 heavy duty vehicles per minute in each of the four lanes.

The ABL is supposed as weakly stable stratified ($\partial T/\partial y = 0$ K/m). As was shown in [20], the stratification plays a minor role in this type of computation. Computational domain is relatively short and the mechanical turbulence caused by passing cars plays the dominant role in the initial mixing of pollutants.

49 different geometrical configuration were simulated. We have tested all combinations of following parameters of vegetation plus case without the vegetation.

• Width: 50m, 80m, 110m, 140m.
• Hight: 3m, 7m, 11m.
• Density 0.25, 0.5, 1.0, 1.5.

3.2 Boundary conditions

• **Inlet:** logarithmic wind profile is prescribed at the inlet with u_{ref} = 5 m/s at height y_{ref} = 10 m, $v = 0$. Roughness parameter z_0 is set to 0.1 m. Homogeneous Dirichlet b.c. for concentration is satisfied. Pressure is extrapolated from the domain, temperature is set to the $T = 20°$.
• **Top:** velocity on the top is given by the Dirichlet b.c., pressure is extrapolated from the domain, concentration $C = 0$ and temperature $T = 20°$.
• **Bottom:** on the ground, the non–slip boundary conditions for velocity component are prescribed. Homogeneous Neumann b.c. for pressure and temperature are supposed, all particles fallen on the ground stay here for all time.
• **Outlet:** Homogeneous b.c. for velocity components, temperature and concentration are supposed. Pressure is prescribed by the barometric formula.

For the turbulence equations, boundary conditions and wall functions according to [18] are used.

3.3 Computational mesh

Computational domain consist of app. 3410^3 cells and it's generated by the *snappyHexMesh*. The mesh is exponentially refined. While on the top of the domain the cell size is app. $2x3$ m, close to the ground and forest it is app. $0.3x0.45$ m. On the ground the boundary layer is made from 3 cells, the first cell is 0.06 m thick.

3.4 Computational results

Typical flow fields are demonstrated in Figure 3. On the left hand side the situation with relatively sparse forest is shown, the flow is decelerated without recirculation. On the other hand, in the case of dense vegetation, massive recirculation zone was developed behind the block.

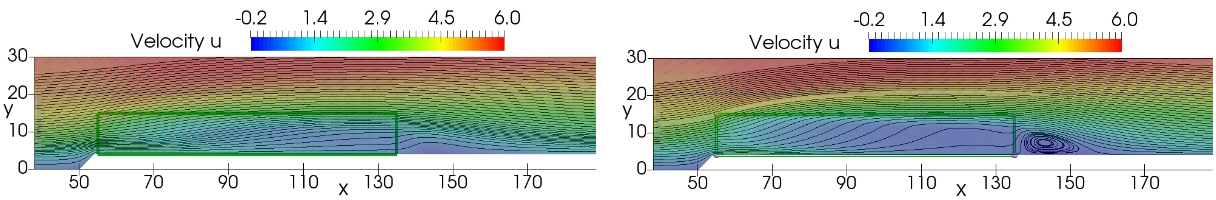

Figure 3: Streamlines for the case of forest 80m wide and 11m high. Density factor 0.5 left and 1.5 right.

The PM concentration in the fixed point $x = 250$m and 3m above the ground is shown in Fig.4 (PM10) and Fig.5 (PM75). In both cases the dependency on the width of vegetation is significant for low vegetation, for high is close to the constant and short forest is sufficient. Unsurprisingly, efficiency is higher for heavier particles, where concentration reduces to $1/9$, whereas to $7/10$ for lighter ones.

Different processes and behavior we can study in Figures 6 - 9, where the horizontal and vertical distributions of pollutant are shown. The horizontal concentrations are drown along the line 3m above the ground, the vertical along the line at $x = 250$m. For the heavier particles

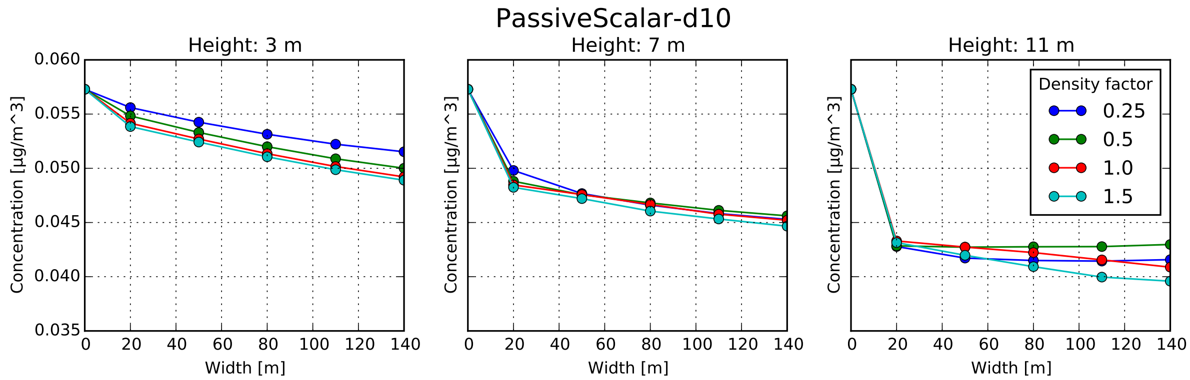

Figure 4: Concentration at $x = 250$m, 3m above the ground for $d = 10$µm

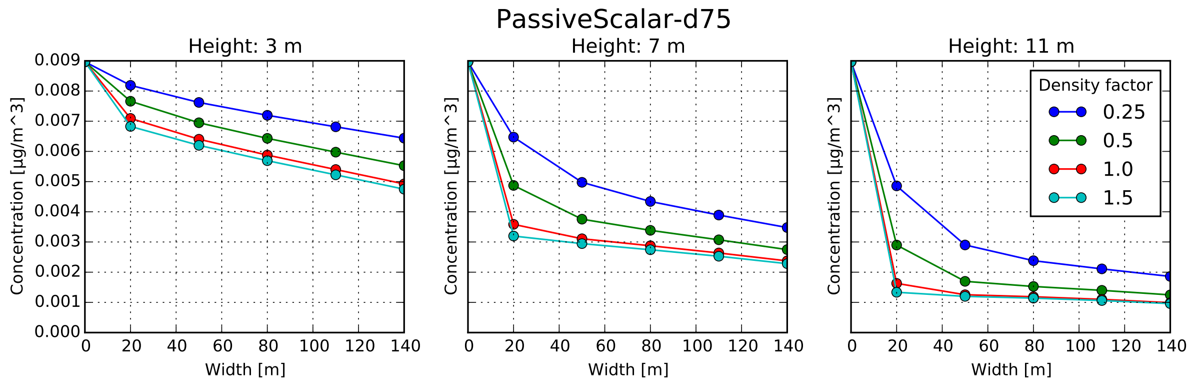

Figure 5: Concentration at $x = 250$m, 3m above the ground for $d = 75$µm

the reduction of concentration is monotonous, see Fig.7. The reduction significantly depends on forest heights, Fig. 9, for low vegetation it is insignificant, for height 11m the reduction for sparse forest is close to the 50%, for dense $80 - 90\%$, for wider forest is close to 90% independently on the density of vegetation. The main effect is the deceleration of the flow inside the vegetation and the consequent longer time for deposition of particles.

The case of lighter, PM10 particles, is more complex, Figs. 6, 8. The monotonical decreasing of concentration is visible for low or sparse vegetation only. The overall effect is however small in those cases. The profile of concentration inside the forest in the case of higher and dense vegetation is different. The recirculation zone close to the forest, the deposition velocity is small (5.5mm/s in comparison to 300mm/s for PM75), the particles accumulate inside the forest. On the other hand the deflection of the flow by the obstacle and increase of the turbulence which leads to spread of the particles to the higher parts of the atmosphere play the major role here. As it is well illustrates in Fig. 8, the reduction of the concentration close to the ground is caused mainly by the transportation of the dust at higher altitudes.

4 Discussion

A method for evaluation of the effects of vegetation barriers on pollution dispersion was developed and used for modeling of the PM10 and PM75 concentration emitted from the highway. In this study effects of height, width and density of leafy vegetation were examined.

Basic processes playing important roles in the deposition and transportation of the particles were identified and shown. The height of vegetation is more important then its length, for higher

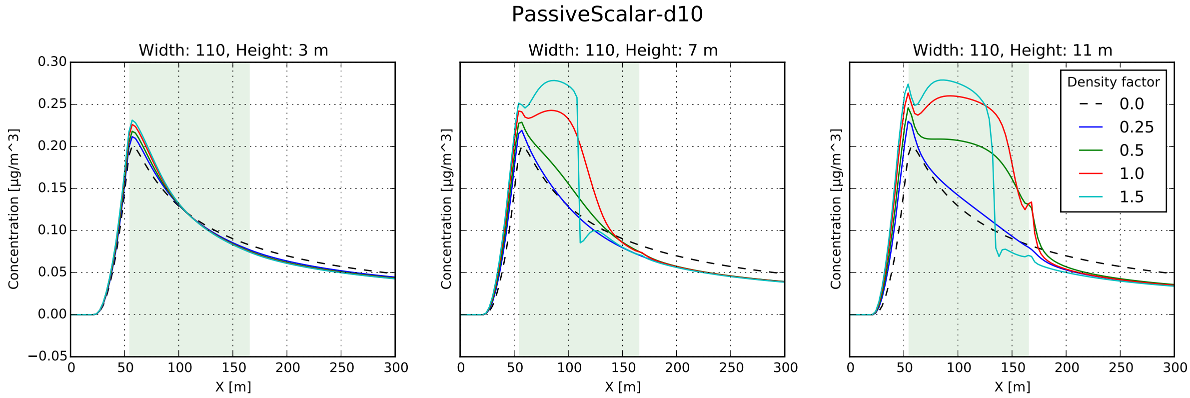

Figure 6: Horizontal profiles of concentration 3m above the ground for $d = 10$µm and block width 110m

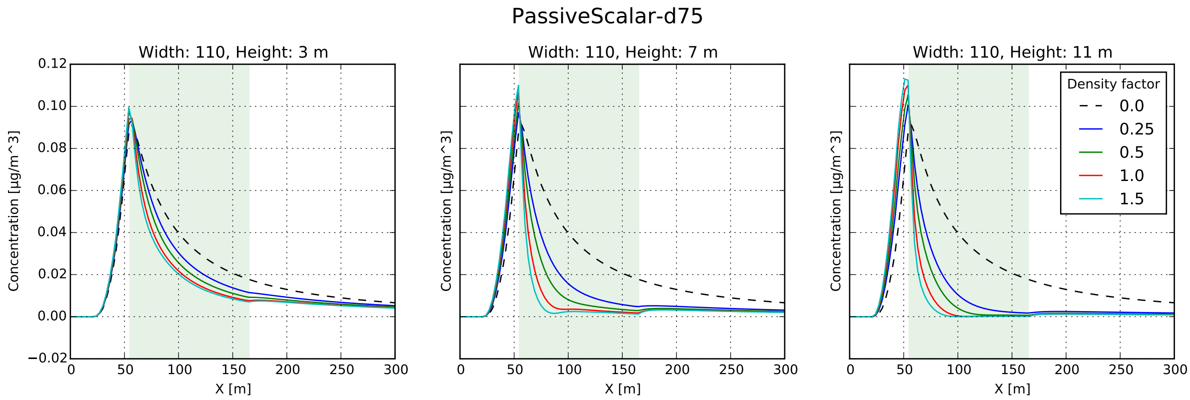

Figure 7: Horizontal profiles of concentration 3m above the ground for $d = 75$µm and block width 110m

forest the dependence on length is insignificant, the low forest is ineffective. The deposition plays significant role for heavier PM75 particles and the vegetation is very efficient due to deceleration of the flow. In the case of lighter PM10 particles, the significant effect is deflection of the flow and increasing of turbulence by the vegetation, which leads to the spreading of pollutant to the higher parts of atmosphere.

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.

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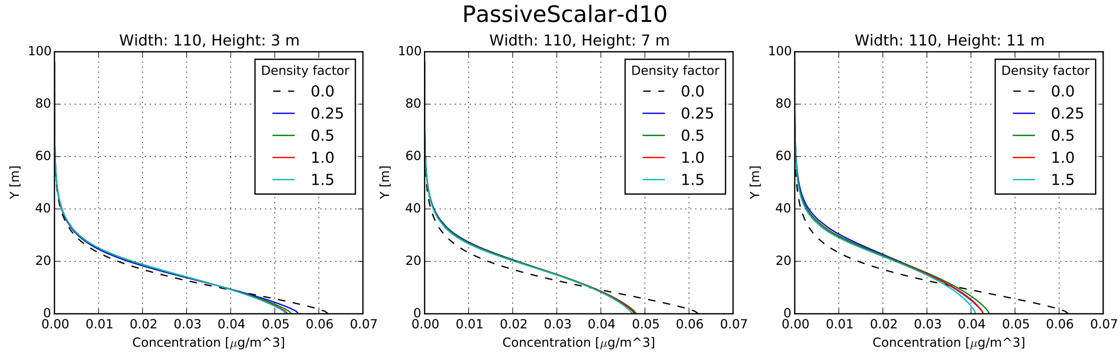

Figure 8: Vertical profiles of concentration at $x = 250$m for $d = 10$μm and block width 110m

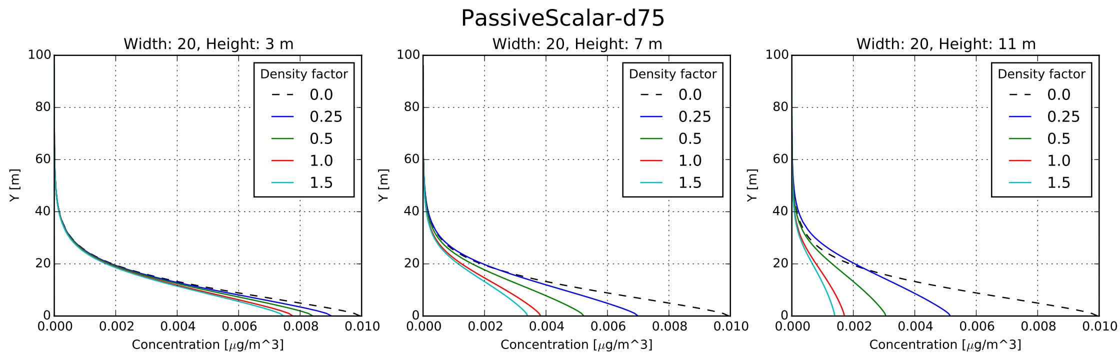

Figure 9: Vertical profiles of concentration at $x = 250$m for $d = 75$μm and block width 20m

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