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INFLUENCE OF VERTICAL DISTRIBUTION OF AEROALLERGENS ON THEIR SPATIAL DISPERSION AND DEPOSITION IN MICRO- AND REGIONAL-SCALE NUMERICAL MODELS

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Abstract: The paper presents part of the research on model development of pollen dispersion and pollen deposition. The Eulerian approach of particle dispersion modelling was engaged for pollen dispersion description. Numerical modelling (CFD code StarCD) was used as the computational code for carried out studies testing three different approaches of pollen deposition in different scale models. The study was done on two studied city areas covering areas of 1 km^2 and 144 km^2.

Key words: *particulate matter, CFD modelling, pollen, dispersion, deposition*

INTRODUCTION

The pollen concentration prediction models are predominantly statistical models analysing the actual meteorological conditions and their history. The simplest models are based only on air temperature monitoring. The outdoor temperature is the basic parameter for prediction of the beginning of the pollen season and it can be used to identify days with a good potential for pollen release. Different approaches are used for determination of the start of the pollen season: i) the sum of daily pollen counts = ∑x criterion (Vliet[1] 2002), ii) the mean temperature method during the pre–defined period (Sparks etal, 2000), iii) the temperature sum method (Jones 1992). Other prediction models analyse another parameters as day light length, morning temperature gradient, relative humidity. The pollen season prediction models are capable to identify the period with good potential for intensive pollination. But, the correct determination of pollen release timing is only the first step to the correct prediction of the pollen concentration in the air. The days with high concentration of pollens in air alternate the days with the low level of pollen concentration during the pollen season. This high variability of the pollen concentration in the air results from change of meteorological conditions, namely precipitation and wind velocity.

The wind velocity directly influences the pollen release rate from mother plants and subsequently the transport of pollen grains. The numerous studies confirmed significant influence of the wind velocity on the air pollen concentration. The threshold velocity of pollination is defined as the lowest wind velocity with evidence of the pollen concentration above the threshold pollen concentration. The threshold velocity of pollination for majority of aeroallergens reaches value in the range from 0.3 till 1 ms^{-1} (Pospisil and Jicha, 2010).The increase of the wind velocity above the threshold velocity of pollination translates into further increase in the pollen maximum concentration until the highest concentration of the pollen season is reached. This trend reflects the increase in the total pollen release rate due to the increase of the air velocity in deeper layers of vegetation and branch bundles. Further increase of wind velocity leads to the decrease of the maximum air pollen concentration due to “dilution” of the canopy layer caused by the vast supply of unpolluted air.

The now-a-day’s pollen concentration prediction models are effectively improved by inclusion of the wind velocity monitoring and the wind velocity prediction. The correct air velocity prediction is the crucial point of numerical models and requires powerful computational methods (for example CFD) that become the common prediction tools of many meteorological models. Inclusion of the wind velocity between the monitored parameters of the pollination models enables to build up the correct prediction regional models with height level of accuracy.

THEORY OF POLLEN MOVEMENT

Pollen dispersion

CFD code StarCD was used as appropriate tool for this study. The set of equations for the conservation of mass and momentum was solved for steady, incompressible turbulent flow. The equation for a general variable ϕ reads

$$\frac{\partial(\rho\varphi)}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i\varphi)=\frac{\partial}{\partial x_i}\left(\Gamma\frac{\partial\varphi}{\partial x_i}\right)+S_\varphi, \qquad (1)$$

where the variable ϕ substitutes a velocity component, concentration of a passive scalar or equals unity in the mass (continuity) equation, ρ is fluid density, u_i is a velocity component, Γ is a general diffusivity coefficient (effective viscosity for the momentum equation and effective diffusion coefficient for the mass equation), S_Φ is a source term.

The wind velocity and direction were imposed on the model with the use of the “wind velocity layer” boundary configuration. This boundary configuration prescribes a specified wind speed and direction at a horizontal layer of air. The air layer is located at height significantly above the building roofs; 45 m above the ground surface in this study. The pressure boundary conditions were prescribed on all sidewalls of the solution domain. The slip wall boundary condition was set on the top of the domain. The k-ε RNG model of turbulence (Yakhot, 1986) was used.

Pollen deposition on smooth surface

Deposition occurs on all solid and liquid surfaces located in a polluted atmosphere. Particles deposition in a boundary layer is described with inclusion of turbulent transport and particle settling (Csanady, 1973).

$$F = K\frac{dC}{dz} + v_S C\,, \qquad (2)$$

where F is the downward mass flux, v_s is the settling velocity of the particles, K is the eddy diffusivity for mass transfer of the species with the concentration C.

The eddy diffusivity is correctly solved by CFD technique in fully turbulent flow. Wall functions substitute the accurate solution of eddy diffusivity in surface boundary layers. Close to the surface, the eddy diffusivity is nearly zero. The Brownian diffusivity of particles greater than 1 μm is near zero too. The downdraft mass flux is then controlled by the deposition velocity (Simpson et al., 2003)

$$v_S = \frac{D_p^2 \rho_p g C_c}{18\mu}\,, \qquad (3)$$

where D_p and ρ_p are respectively the particle diameter and particle density, μ is the air dynamic viscosity, g is the gravitational acceleration, C_c is the slip correction factor expressed as (Simpson et al., 2003)

$$C_C = 1 + \frac{2\lambda}{d_p}\left[1.257 + 0.4\exp(-\frac{1.1 d_p}{2\lambda})\right], \qquad (4)$$

where λ is the mean free path of gas molecules.

Pollen deposition on vegetation

Deposition of pollen grains is very frequent on surfaces with a vegetation cover. Due to the very complex geometry of vegetation, an appropriate simplification must be used for calculation of pollen grains deposition. The deposition velocity is the most frequently obtained from experimental studies with different types of vegetation (Petroff, A., 2004). The experimental deposition velocity is then used in transport equations of mathematical description. Total deposition of all pollen grains is assumed on the vegetation cover. This assumption can be used due to very low wind velocity at foliage or grass.

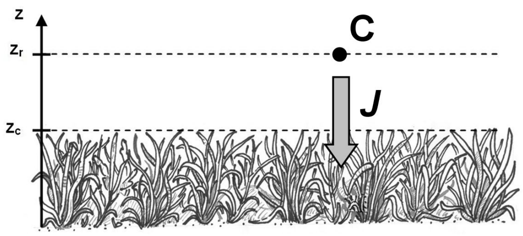

Figure 1. Illustrative expression of simplified description of pollen grain deposition on surface with grass cover.

The deposition velocity can be considered only in vertical direction on vast lawns in stable wind conditions. The deposition velocity is expressed by Equation (5) as ratio of deposition mass flux of pollen grains J to pollen grain concentration C in the free stream above vegetation z_r, see Fig. 1

$$v_d = \frac{J}{c(z_r)}\,. \qquad (5)$$

SIMPLIFIED APPROACHES OF DEPOSITION DESCRIPTION IN NUMERICAL MODELS

Three different approaches were tested for mathematical description of pollen deposition on vegetation and the ground surface. The tested approaches respect the deposition theory mentioned above.

Deposition velocity prescribed in accordance with sedimentation velocity – approach "A"

This approach is used for assignment of the pollen grains deposition in the mathematical model. The source terms are used for prescription of the deposition rate in the finite control volumes immediately adjacent to the observed surface areas in the model. The source term expresses the loss of pollen grains in the particulate control volume. The key point of this approach is correct quantification of the source terms. The equivalence between sedimentation velocity and deposition velocity of pollen grains presents the basic characteristic of this approach.

Zero pollen concentration prescribed on ground surface – approach „B“

This approach considers deposition of pollen grains by sedimentation velocity in accordance with the approach „A“. In addition to this, the approach „B“ considers contribution of turbulent diffusion on pollen grain transport in the ground surface area. For this purpose, the zero concentration boundary condition is assigned on the ground surface. This boundary condition represents deposition of all pollen grains in contact with the ground surface (driven either by sedimentation velocity or by turbulent diffusivity).

Deposition considered in accordance with experimental deposition velocity – approach „C“

This approach utilizes deposition velocity obtained from different experimental studies. Only the mass source terms for finite volumes are used for prescription of deposition rate in the finite control volumes immediately adjacent to the observed surface in the model.

MICRO-SCALE MODEL

Model description

The computational domain represents the idealized part of the city formed by residential buildings with large gardens. The computational domain ground dimensions are approximately 1 × 1 km. The height of the modeled buildings is 10 m. The distance between buildings is 10 - 15 m, see Fig. 2 and Fig. 3. The numerical model was built up from layers of control volumes with the height 0.25 m. The pollen grains were simplified by spherical particles with corresponding aerodynamic diameter. Density of the pollen grains is 1.2 g/cm^3.

Model setting

Boundary conditions were assigned to all boundary surfaces and appropriate source terms were assigned to the specified control volumes as mentioned below:

- The ground surface – “Non slip wall” with parametrical roughness 0.2 m
- The windward side wall – “Inlet” with wind velocity profile , $u=u_0*(z/z_0)^{0,23}$
- The leeward side wall – “Pressure” boundary condition with defined static pressure value
- The top surface – “Slip wall” boundary condition
- The pollen source term is prescribed as volume source term in control volumes located in position of trees and lawns.

Figure 2. Illustrative view of residential area in the city of Brno

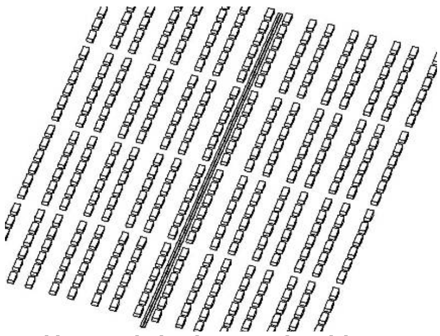

Figure 3. Buildings in idealized numerical model

Results

The built up micro-scale model was used for parametrical studies focused on final air pollen concentration obtained for wind velocity 2 m/s and 4 m/s at height 10 m above the ground. Production of pollen grains from grass and trees was solved separately with taking into consideration differences in pollen geometry and vertical characteristics of distribution. Deposition of pollen grains on the ground surface was solved with utilizing three different approaches described above: “A” - Deposition velocity prescribed in accordance with sedimentation velocity, “B” - Zero pollen concentration prescribed on ground surface, “C” - Deposition considered in accordance with experimental deposition velocity.

The first parametrical study was carried out for grass pollen grains. The deposition of the pollen was considered on entire ground surface of the numerical model. The pollen production source term was assigned to control volumes located between the ground surface and the layer at height 0.25 m. The pollen characteristics were prescribed in accordance with parameters of major grass aeroallergens. The sedimentation velocity was considered 0.0085 m/s (Chamberlain, A., 1975). The experimental deposition velocity was 0.28 m/s (Chamberlain, A., 1975).

The second parametrical study was carried out for pollen grains pollinating from trees. Deposition of pollen grains was considered on the entire ground surface. Pollen grain production was prescribed in positions of considered trees with regular spacing in accordance with spacing of the buildings. Two virtual trees was considered to each building. The virtual tree is substitute by rectangular block of control volumes with height 4 m and top view dimension 2×2 m. The pollen characteristics were prescribed in accordance with parameters of major tree aeroallergens – group betula. The sedimentation velocity was considered 0.024 m/s.

The mean air pollen grain concentrations were identified in both parametrical studies. The results are presented in form of graph on Fig. 4.

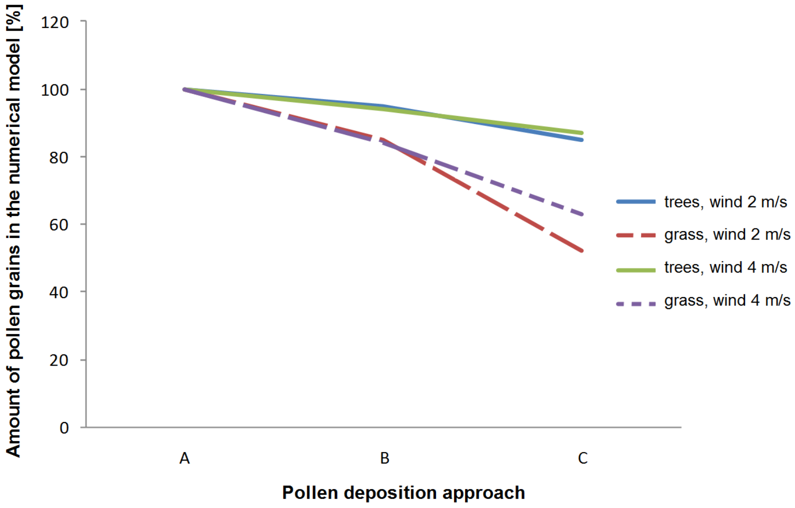

Figure 4. The mean air pollen grain concentrations obtained on the micro-scale numerical model

REGIONAL-SCALE MODEL

Model description

The regional-scale model involves the city of Brno (pop. 400 000) and its nearby vicinity. The solution domain covers an area of 12×12 km. Due to large modeled area, it is impossible to accurately involve geometry of all objects. The parametrical roughness is used as a convenient substitution of the surface geometry details. The primary ground surface was build up in accordance with the actual terrain profile. The regional model ground plan was divided in 576 square control regions with the side length of 500 m. A convenient parametrical roughness was assigned to these regions. The primary ground surface was refined at terminal control volumes size with the top view dimensions 50×50 m. The 900 m high air layer was modeled above the primary ground surface.

The inlet/outlet boundary conditions were assigned on side walls of the regional model. The wall boundary condition with appropriate parametrical roughness was assigned to the ground surface. The “slip wall” condition was assigned to the top of the domain. K-ε RNG model of turbulence was used. Pollen grains deposition was considered on all surfaces.

Results

The built up regional-scale model was used for parametrical studies focused on final air pollen concentration obtained for wind velocity 2 m/s at height 10 m above the ground. Production of pollen grains was solved separately for grass, bushes and trees with taking into consideration differences in pollen geometry and vertical characteristics of distribution. Deposition of pollen grains on the ground surface was solved with utilizing tree different approaches described above: “A”, “B”, “C”. The pollen grain production was considered in same way as described in previous study. The source terms were prescribed in control volumes in corresponding control regions reflecting the height of pollinating vegetation. The height of the grass was considered 0,25 m, height of the bushes 1 m and height of trees 4 m. The sedimentation velocity was considered 0.0085 m/s for pollen from grass, 0.024 m/s for pollen from bushes and 0,016 m/s for pollen from trees. The experimental deposition velocity was considered 0.044 m/s on surfaces covered by trees, 0.036 m/s on surfaces covered by bushes and 0.028 m/s on surfaces covered by grass (Chamberlain, A., 1975).

The mean air pollen grain concentrations were identified in the parametrical study. The results are presented in form of graph on Fig. 5.

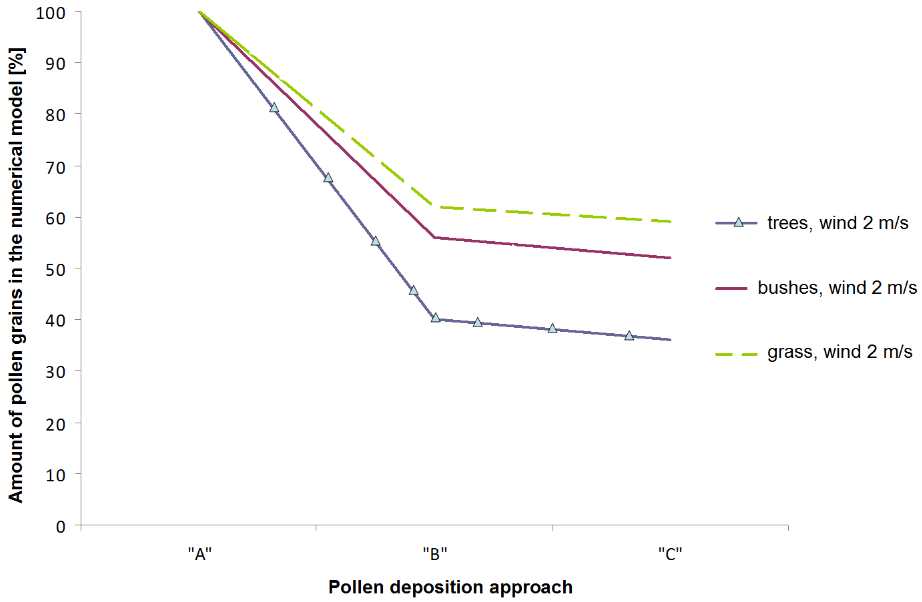

Figure 5. The mean air pollen grain concentrations obtained on the regional-scale numerical model

CONCLUSION

The results of carried out parametrical studies show significant influence of turbulent diffusion on the pollen deposition flux in boundary layer of surfaces with vegetative cover. More intensive deposition results in lower pollen grain concentration in the air. Utilizing of experimental deposition velocity provided the lowest pollen air concentration in both tested numerical models.

For the micro-scale model, the idealized approaches of deposition velocity based only on common transport equations in boundary layer above flat surface overestimate pollen concentration in the air obtained with consideration of experimental deposition velocity. For regional-scale model, very close values of air pollen concentration was obtained by approaches taking into account experimental deposition velocity or pollen transport by turbulent diffusion in the boundary layer.

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