NUMERICAL MODELING OF STREET CANYON PARTICLE RE-SUSPENSION DRIVEN BY GROUND AIR VELOCITY AND KINETIC ENERGY OF TURBULENCE

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INTRODUCTION

Many big cities are often heavily polluted by airborne particles released by road traffic. The highest concentrations of PM are generally present in inner parts of urban areas, especially at a close vicinity of major traffic paths. Street particulate matter consists from complex mixture of motor vehicle exhaust particles, tire dust, brake lining wear dust, soil dust, road surface dust and other biological materials. Many different parameters influence formation, transport and deposition of particles at these locations. Particles behavior is influenced by transportation in moving air, settling due to gravity, interaction with buildings walls, deposition on a ground surface and re-suspension of once deposited particles that are lifted by a local air movement and dispersed into surroundings. Therefore, particles behavior is very complex process difficult for an accurate mathematical description. The numerical modeling represents the only tool capable to take into account detail geometry of urban areas, detail description of relevant PM sources and the interaction between moving cars and ambient air (Jicha et al., 2000). Advanced numerical modeling tools are necessary to correct prediction of detail air velocity fields in calculated domains and description of the dispersion processes in urban areas.

It is impossible to accurately quantify production of all real PM sources in urban areas. From different studies (*Moussiopoulos N. et al.,* 2003) follows that re-suspension of once deposited particles is the most intensive source of urban airborne particles during "dry periods". The re-suspension process of once deposited particles depends on an actual air velocity field above the ground surface, a local slit load, a surface roughness, particle geometry and other particle parameters. Coarse particles (d > 2.5 μm) are very often able to re-suspend from dry-surfaces. On the other side, fine particles and ultra fine particles show only limited tendency to re-suspension from all surfaces. This results from significant amount of a liquid fraction forming particles smaller than 2.5 μm and existence of the Van der Waals force between ultra-fine solid particles and surfaces. Re-suspension of particles is generally impossible from wet and adhesive surfaces.

From above mentioned follows that the re-suspension process is very complex process and its mathematical description is generally connected with high value of uncertainty. The utilized numerical models for prediction of PM concentration fields in urban areas falls in two categories: a detail solution of PM dispersion processes with simplified quantification of PM sources (*Flemming, J.*, 2003) and a solution of concentration fields for gas species (NO_x) with known correlation to PM (*Kukkonen, J. et al.*, 2001).

This paper focuses on the numerical modeling of re-suspension of once deposited particles that are lifted by moving air and dispersed into surroundings. The paper presents a simplified approach to quantification of the particle re-suspension in a vicinity of traffic paths. The CFD code StarCD was used to build up the numerical model of the studied area and process the calculations. We considered PM10 spherical particles with density 300 kg/m^3.

PARTICLE RESUSPENSION

The re-suspension of particles settled on surfaces results from interaction of aerodynamic, electrostatic and mechanical forces. The Saffman lift force due to a velocity gradient near walls is one example of the aerodynamic interaction. This lift force is oriented perpendicularly to a direction of flowaffecting deposited particles in a viscous fluid.

An electro static force on the charged particles can be calculated only for the known particle charge and the magnitude of electric field. This information is not common for dispersion studies and the electro static force is commonly excluded from calculations. The turbulent intensity of a stream can also influence the air drag force affecting particles (*Punjrath J.S.*, 1972). The Saffman lift force and the fluid turbulence are sufficient to suspend fine and ultra fine particles. Coarse particles are often moved by the drag force along the surface. The drag force affecting particles in boundary layer was expressed (*Punjrath J.S.*, 1972) in form

$$F_d = \frac{p d^2 C_{fx} r U^2}{8} , \qquad (1)$$

where C_{fx} is the local shear stress coefficient, r is the air density, U is the free-stream air flow velocity. An irregular shape of particles together with a surface roughness cause irregular bouncing of particle against walls. This behavior prepares good conditions for following lift up of particles in a boundary flow.

Various forms of equations can be found in literature for determination of the windblown dust flux. An algorithms solve the dust flux from either the wind velocity and the threshold wind velocity (equation 2) (*Tegen and Fung*, 1994) or the friction velocity and the threshold friction velocity (equation 3) (*Claiborn et al.*, 1998).

$$F = C_{TF} u^2 (u - u_t) , \qquad (2)$$

where F is the dust flux, u is the wind velocity, u_t is the threshold wind velocity and C_{TF} is the constant representing character of soil surface (disturbed/undisturbed).

$$F = C u_*^3 a_g \left(u_* - u_{*t}\right), \qquad (3)$$

where a_g is the constant expressing effect of non-instantaneous wind velocity (~ 1.2), u_* is the friction velocity, u_{*t} is the threshold wind velocity and C is an empirical constant.

The friction velocity for a neutrally stable atmosphere can be determined in a couple of ways. From the logarithmic wind velocity profile, the wind velocity is related to the friction velocity as

$$u = \frac{u_*}{k} \ln\left(\frac{z - d}{z_0}\right), \qquad (4)$$

where k is the von Karman constant (~ 0.4), z_0 is the aerodynamic roughness length and d is the displacement height.

The critical point of the particle re-suspension numerical modeling is to correctly determine the threshold velocity above all surfaces in a calculated domain. The threshold velocity is highly variable and is a function of surface conditions and flow characteristic.

STREET CANYON STUDY

The following section presents the study focused on determination of the PM10 threshold velocity in a street canyon with two-way traffic.

Studied domain description

An urban area in the center of the city of Brno was used as the appropriate domain for this study. The solution domain dimensions are approximately 1 x 1 km. The domain includes one long street canyon Kotlarska Street and 4 streets that cross perpendicularly the main road. Traffic in the perpendicular streets is significantly lower compared with the main street (20000 cars/day). Kotlarska Street is fed by heavy traffic that comes from two intersections located at solution domain borders. Five-storey buildings (20m high) form this part of the city. Kotlarska street represents 22 m-wide street canyon with an aspect ratio 1.1 (width/height). Two-way traffic in total four traffic lanes is present in Kotlarska Street. The computational model is formed by blocks of buildings with internal yards that are common at this part of the city. Beyond these blocks, a parametric roughness is used to model the area outside the detail-modeled part of the solution domain.

Threshold velocity determination

Many studies offer an expression of the threshold velocity for a particular type of surface and a specific wind velocity profile above the ground surface. The wind velocity profile above the surface is mostly considered as the natural logarithmic wind velocity profile. A corresponding threshold wind velocity is compared with an air free stream velocity. This approach is convenient for determination of dust re-suspension from flat surfaces in open space.

An assessment of re-suspension process in urban areas is more complex due to complexity of an air velocity field in a vicinity of a ground surface. An air velocity field in the studied domain is mainly influenced by the buildings geometry and a cars movement in the main street canyon. The CFD code StarCD was used as appropriate tool capable of correct air velocity field prediction in small-scale urban areas. A computation model was built up from finite hexahedral control volumes of an appropriate geometry. The control volumes with height 0.7 m were used just above the ground surface. A calculation process solves an air velocity in central nods of the control volumes (0.35 m above ground surface). A wind velocity profile is substituted by the logarithmic wind velocity profile between these central nods and a ground surface.

New approach for fast assessment of re-suspension existence was developed. The air velocity predicted in the central nods of control volumes just above the ground surface was compared with the threshold air velocity obtained by modification of early expressed formulation for re-suspension of coarse particles in open space. With respect to detail geometry of a ground surface of the studied street canyon, we specified the threshold wind velocity in height of 0.35 m as $u_t^{0.35} = 0.56$ m/s for spherical PM10 particles with density 300 kg/m^3. Two different calculations of air velocity field were carried out on the solution domain for parameters mentioned in the tab. 1.

Table 1. Input parameters of carried out calculations.

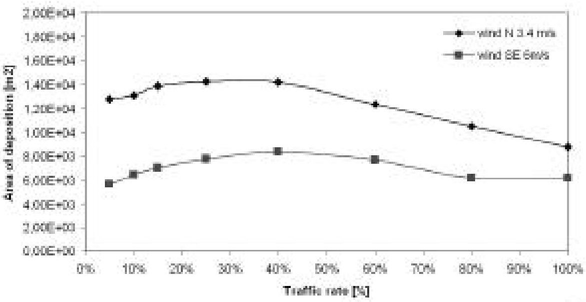
Variant	Wind direction	Wind velocity [m/s]	Traffic rate [cars/hour/lane]
Wind N 3.4 m/s	North	3.4	383
Wind SE 6 m/s	South-East	6.0	384

If the predicted wind velocity value is lower than the threshold wind velocity value, particles deposit on the surface without a possibility of re-suspension. The fig. 1a shows the obtained relation between "the deposition area" in the studied main street canyon and the traffic rate. In this case, only a horizontal component of velocity was considered. The fig. 1a shows increase of the deposition area for traffic rate increase from 0% to 40%. This behavior results from the interaction of moving cars with an actual air velocity field. First, a car movement forces the air in a different direction than resulting from a pure wind blowing. Second, significant production of turbulence in a close vicinity of moving cars causes an increase of the turbulent viscosity. Higher turbulent viscosity slows down a velocity of air flow field in the street canyon, especially in boundary layers. An intensive car movement predominantly influences air velocity field for traffic rate in the range from 40% to 100%. A traffic rate increase causes decrease of the deposition area at this range.

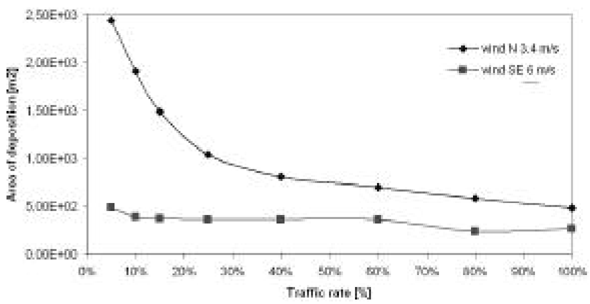
The kinetic energy of turbulence is parameter quantitatively expressing a turbulent character of an air flow. The kinetic energy of turbulence represents another parameter with a strong influence on particle re-suspension. From this reason, we expressed the driving velocity as a sum of a mean air velocity and a fluctuation velocity component

$$u_d = u + \sqrt{\frac{2k}{3}} \quad , \qquad (5)$$

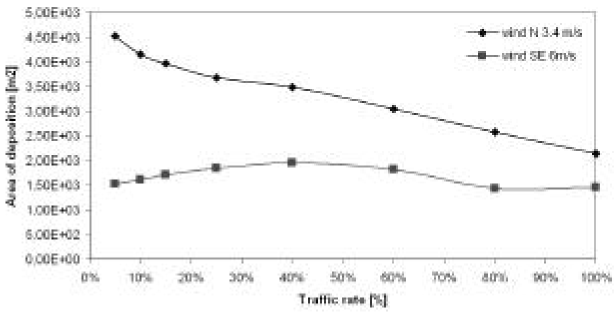
where u is the horizontal component of the mean air velocity and k is kinetic energy of turbulence. The driving velocity in central nods of control volumes located just above the ground surface was compared with the threshold wind velocity. The fig. 1b shows result of that comparison expressed as a relation between the deposition area and the traffic rate.



a)



b)



c)

Fig. 1; The relation between the deposition area and the traffic rate:
a) expressed as function of the horizontal velocity
b) expressed as function of driving air velocity (equation 5)
c) expressed as function modified driving air velocity (equation 6)

Inclusion of kinetic energy of turbulence unrealistically decreases the deposition area in the studied street canyon but conveniently influences re-suspension process on the road surface and in its close vicinity. From these reasons, we tested different expressions of the driving velocity. The most realistic results (see fig. 1c) were obtained with the driving velocity in the form

$$u_d = u + 0{,}7\sqrt{\frac{2k}{3}}\,. \qquad (6)$$

CONCLUSION

This paper introduces the numerical modeling of re-suspension of once deposited particles in the studies street canyon located in a large urban area. The CFD code StarCD was used to build up the numerical model of the studied area and perform the calculations. We considered PM10 spherical particles with density 300 kg/m^3. An air velocity predicted in the central nods of control volumes just above the ground surface was compared with the threshold re-suspension air velocity. With respect to detail geometry of a ground surface of the studied street canyon, we specified the threshold wind velocity at height of 0.35 m as 0.56 m/s. Three different variants of the driving air velocity calculations were tested. First, only a horizontal component of an air velocity was considered. Second, the driving velocity was expressed as a sum of a mean air velocity and a fluctuation air velocity component. The most realistic results were obtained with the driving velocity expressed as a sum of a mean air velocity and 70% of the fluctuation air velocity component.

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