DETERMINATION OF THE PM10 URBAN THRESHOLD VELOCITY OF RE-SUSPENSION IN AN INNER PART OF URBAN AREA

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Abstract: In this paper authors focus on determination of the threshold velocity of re-suspension for particles 10 m in an urban street canyon with two-way traffic. The urban wind threshold velocity of re-suspension is derived from a long-term measurement carried out in the city of Brno. A numerical modelling based on the finite volume method is used for a detail study of the relation between a wind velocity above buildings roofs and an air velocity just above the ground surface. The predicted threshold air velocity of re-suspension at the bottom part of the studied street canyon is compared with two theoretical studies on particle re-suspension. Calculations are carried out for perpendicular, longitudinal and oblique (45°) wind direction with and without inclusion of traffic dynamic. To simulate traffic, an original model developed previously by the authors is used that takes into account traffic density, speed of cars and number of traffic lanes.

Key words: *particulate matter, CFD modelling, particle re-suspension, street canyon.*

1. INTRODUCTION

Many big cities are often heavily polluted by airborne particles released by road traffic. The highest concentrations of PM (particulate matter) are generally present in inner parts of urban areas, especially at a close vicinity of major traffic paths. Street PM 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, deposition and re-suspension of particles at these locations. Particles movement 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 a surrounding. Therefore, particles movement is very complex process difficult for an accurate mathematical description. Advanced numerical modelling tools are necessary to correct prediction of detail air velocity fields in calculated domains and description of the dispersion processes in urban areas. The numerical modelling represents the only tool capable to take into account detail geometry of urban areas and the interaction between moving cars and ambient air (Jicha et al., 2000).

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 can be 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, surface roughness, particle geometry and other particle parameters. Coarse particles (d>2.5 m) 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 m and existence of the Van der Waals force between ultra-fine particles and surfaces. Re-suspension of particles is generally impossible from wet and adhesive surfaces. From above mentioned follows, the re-suspension process is very complex process and its mathematical description is generally connected with high value of uncertainty. The numerical models for prediction of PM concentration fields in urban areas falls in two categories: i) detail solution of PM dispersion processes with simplified quantification of PM sources (Flemming, J., 2003) and ii) solution of concentration fields for gas species (e.g. NO_x) with known correlation to PM (Kukkonen, J. et al., 2001).

At the presented study we used the first type of numerical model with focus on the numerical modelling of re-suspension of once deposited particles that are lifted by moving air and dispersed into surroundings. This paper presents the study focused on determination of the PM10 re-suspension threshold velocity in a street canyon with two-way traffic. The CFD (Computational Fluid Dynamics) code StarCD (developed by CD-adapco) was used to build up the numerical model of the studied area and process the calculations. We considered PM10 spherical particles with density 1200 kgm^{-3}.

2. PARTICLE RE-SUSPENSION

The re-suspension of particles settled on surfaces results from interaction of aerodynamic, electrostatic and mechanical forces. The Saffman lift force (Iversen et al., 1982) due to a velocity gradient near walls is one example of the aerodynamic interaction. This lift force is oriented perpendicularly to a direction of flow affecting deposited particles in a viscous fluid.

An electro static force on the charged particles can be calculated only for a known particle charge and the magnitude of electric field. This information is not common for dispersion studies and an electro static force is commonly excluded from calculations. The turbulent intensity of a flow can also influence the air drag force affecting particles (Punjrath J.S., 1972). The Saffman lift force and the fluid turbulence are sufficient for re-suspension of fine and ultra fine particles. Coarse particles are often moved by the drag force along the surface (Punjrath J.S., 1972). An irregular shape of particles together with a surface roughness causes irregular bouncing of particle against surface. This movement provides good condition 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. Numerical models determine particle re-suspension flux either as the function of a wind velocity and a threshold wind velocity (Eq. 1) (Tegen and Fung, 1994) or as the function of a friction velocity and a threshold friction velocity (Eq. 2) (Claiborn et al., 1998).

$$F = C_{TF} u^2 (u - u_t) \tag{1}$$

where F is the particle 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).

$$F = C u_*^3 a_g \left(u_* - u_{*t}\right) \tag{2}$$

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 the empirical constant.

The friction velocity for a neutrally stable atmosphere can be determined from the equation of the logarithmic wind velocity profile,

$$u = \frac{u_*}{k} \ln\left(\frac{z-d}{z_0}\right) \tag{3}$$

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 modelling is to correctly determine a threshold velocity of re-suspension in a calculated domain. The threshold velocity of re-suspension is highly variable and is a function of surface conditions and flow characteristic.

3. URBAN THRESHOLD VELOCITY OF RE-SUSPENSION

The urban threshold velocity of re-suspension is the lowest velocity of air at height 10 m above the ground, for which the re-suspension represents a significant contribution in an urban air PM10 concentration. The urban threshold velocity of re-suspension is strongly influenced an actual geometry of an urban area, air density and geometry of particles. It is necessary to obtain a corresponding urban threshold velocity of re-suspension for each particular urban area.

The centre of the city of Brno (population 400000) was used as a convenient study domain. Data from PM10 long-term measurement in the city of Brno were used for determination of the urban threshold velocity of re-suspension. As the first step, we derived the relation between air velocity and PM10 concentration measured during year 2005 in the studied urban area, see (Fig.1). The second step involved a detail analysis of the relation and determination of the PM10 urban threshold velocity of re-suspension in this area. For this purpose, we analyzed the trend of the relation on the Figure 1. Without presents of re-suspension, the relation can be assumed as a smooth regularly decreasing curve. The real relation shows significant changes in the trend. These changes of trend are connected with changes of particle production in the urban area. And the re-suspension is the only particle urban production connected with a wind velocity. In the Figure 1, the air velocity range with a significant contribution of re-suspended particles is indicated. The wind velocity 2.4 m (height 10 m) was determined as the urban threshold velocity of re-suspension with significant influence on urban PM10 concentration. This threshold velocity fully corresponds with previous studies carried out in urban areas.

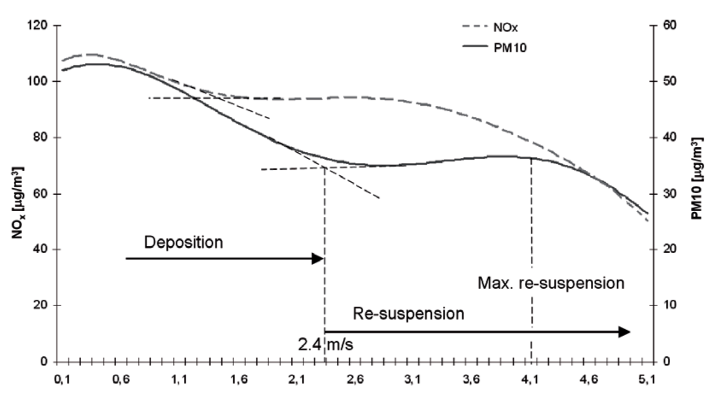

Figure 1. The relation between the air velocity and the PM10 concentration measured during year 2005.

4. STREET CANYON THRESHOLD VELOCITY OF RE-SUSPENSION

An assessment of the 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 previous section discussed the urban threshold velocity of re-suspension with utilizing of the driving wind velocity above a "buildings roof" level. But small scale models describing dispersion of pollutants in street canyons require much more detail approach to correct description of re-suspension. In this study we focussed on the particular street canyon in the city of Brno. The numerical model of the studied canyon was build up. Series of calculations were carried out with focus on detail description of an air flow above a ground and a road surface.

Computational domain description

The computational domain ground dimensions are approximately 0.5 x 0.5 km. The domain includes one main street canyon, Kotlarska Street, and 4 streets that cross the main road, see the Figure 2. Traffic in the perpendicular streets is significantly lower compared with the main street and it was neglected in the numerical model. Kotlarska Street is fed by heavy traffic (20000 cars/day) that comes from two intersections located at the solution domain borders. Two-way traffic in total four traffic lanes runs in Kotlarska Street. Five-story buildings (20 m high) form this part of the city. Kotlarska Street represents 22 m wide street canyon with an aspect ratio 1.1 (width/height). The computational domain 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-modelled part of the computational domain.

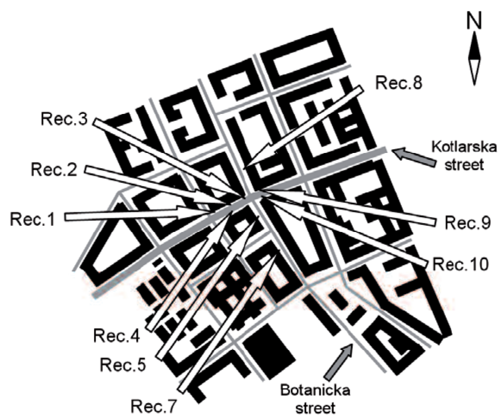

Figure 2. Top view of the computational domain.

Numerical model

CFD code StarCD was used as appropriate tool for this study. The set of equations for the conservation of mass, momentum and passive scalar was solved for steady, incompressible turbulent flow. The equation for a general variable has the form (Milne-Thompson, L.M., 1968)

$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\phi\right)=\frac{\partial}{\partial x_i}\left(\Gamma\frac{\partial\phi}{\partial x_i}\right)+S_\phi+S_\phi^P \tag{4}$$

where the variable ϕ substitutes a velocity component, concentration of 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 term (effective viscosity for the momentum equation and effective diffusion coefficient for the mass equation), S_Φ is a source term and S_ϕ^P is an additional source term. The additional source term S_ϕ^P results from the interaction between continuous phase (air) and discrete moving objects (cars).

A wind velocity and a wind direction were set up on the model with utilizing of the “wind velocity layer” boundary configuration. This boundary configuration prescribes a specified wind speed and a wind direction at a horizontal layer of air. The air layer is led at height significantly above the building roofs, 45 m above the ground 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.

To simulate traffic, an original model (Jicha et al., 2000) developed previously by authors is used that takes into account traffic intensity, speed of cars and number of traffic lines. The k-ε RNG model of turbulence (Yakhot, 1986) was used. As it is known, moving objects induce a strong kinetic energy of turbulence that should be added as an additional source S_k to the k-equation. From different studies e.g. Eskridge and Hunt (1979), Sedefian et al. (1981)

and Sini & Mestayer (1997), it follows that turbulence is induced mainly in the wake behind the vehicle. Therefore the additional source S_k (Eskridge and Hunt, 1979) was added only along the trajectory that cars follow.

$$S_k = C_c\left(U_{car} - U_\infty\right)^2 \dot{Q}_{car} \tag{5}$$

where Cc is a model constant, U_{car} is a car speed, U_∞ is an air velocity and Q_{car} is a traffic rate with the unit carss^{-1}.

Determination of the street canyon threshold velocity of re-suspension

The urban threshold velocity of re-suspension was used for setting up of boundary conditions of the numerical model. We considered 3 different wind directions, namely: perpendicular, longitudinal and oblique (45°) to the main street canyon. Six different calculations were carried out at all, three for situations without inclusion of moving cars and three with inclusion of moving cars.

Moving cars force the air in a different direction than results from a pure wind blowing. Significant production of turbulence in a close vicinity of moving cars causes an increase of turbulent viscosity. Higher turbulent viscosity slows down a velocity of air flow field in the street canyon, especially in boundary layers.

The air velocity predicted just above a ground surface was used for following assessment as a representative value directly influencing re-suspension. The 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 solved 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.

The Fig. 3 shows results of a numerical prediction in the form of the relation between the air velocity at height 0.35 m above the ground surface and the area of the studied street canyon affected by equal or lower air velocity. In the Figure 3, we can clearly see the air velocity range 0.25 ms^{-1} to 1.2 ms^{-1}, where a small change of an air velocity causes a significant change of the affected area. This behaviour provides good conditions for significant particle re-suspension during increasing of a wind velocity. Because the range of "sensitive" velocities is quite wide, we use the average velocity value as the corresponding threshold velocity. The street canyon threshold velocity of re-suspension was determined as 0.75 ms^{-1} (at height 0.35 m).

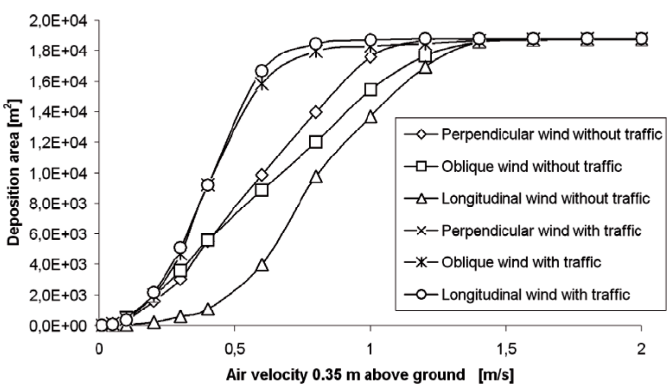

Figure 3. The predicted relation between the air velocity at height 0.35 m and the area of the studied street canyon affected by equal or lower air velocity.

Comparison with other studies

Different studies on determination of the threshold velocity of particle re-suspension were carried out in recent years. Majority of these studies considered particle re-suspension from a flat horizontal surface that fit well to detail solution of a bottom part of the studied street canyon. We compared the predicted street canyon threshold velocity of re-suspension with results derived from formulations published by Cornelis and Gabriels (2004) and Saho and Lu (2003). In all cases, we considered spherical particles with diameter 10 μm, density of particles 1200 kgm^{-3}, parametrical roughness of surface 0,0003 m and wind profile displacement 0 m. From the Cornelis and Gabriels (2004) formulation, we derived the threshold velocity of re-suspension 0.724 ms^{-1}. From the Saho and Lu (2003) formulation, we derived the threshold velocity of re-suspension 0.957 ms^{-1}.

5. CONCLUSION

The predicted street canyon threshold velocity of re-suspension 0.75 ms^{-1} for PM10 particles showed good agreement with the mentioned theoretical studies. Utilizing of CFD for detail small scale modelling in urban areas is perspective application enabling correct assessment of re-suspension from ground surface in urban areas with complex geometry. Carried out calculations confirmed the relation between the urban threshold velocity of re-suspendion (above building roofs) and the street canyon threshold velocity of re-suspension (at boundary layer just above the ground surface).

Presented numerical modelling can be successfully used even for inverse assessment of the urban threshold velocity of re-suspension in a particular urban area based on theoretical studies on PM re-suspension from a horizontal layer.

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