SMALL SCALE PM DISPERSION MODELING IN THE INNER PART OF AN URBAN AREA

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INTRODUCTION

Local vehicular traffic is responsible for a substantial fraction of street-level concentration of PM10 due to primary emissions and vehicle driven material from street surfaces. PM concentration the most frequently overcomes threshold values namely along major traffic paths and in a surrounding of important city intersections. Fine PM particles may be causing a significant burden of disease and excess deaths. From this reason, cities are generally the most affected areas with critical concentration of airborne particulate matter. City air quality control systems require correct information about PM dispersion processes for effective control of air quality.

Particulate behavior is primary driven by actual air velocity field. Therefore, correct prediction of PM dispersion can be done only with utilizing of an appropriate mathematical model that provides correct air velocity field at canopy layers of heavily built up urban areas. This tool must be capable to take into account actual meteorological conditions together with traffic related parameters. Moving vehicles enhance both micro- and large-scale mixing processes in their surrounding. Therefore, the traffic must be taken into account for correct description of mixing processes in the proximity of traffic paths.

CFD code StarCD was used in this study as an appropriate tool that is capable of correct velocity field prediction at small-scale numerical models. Different options of CFD technique and different convenient approaches were tested. To simulate traffic, an original model (*Jicha M.*, *Katolicky J.*, *Pospisil J.*, 2000) developed previously by the authors is used that takes into account traffic density, speed of cars and number of traffic lanes. The numerical predictions were compared with measurement carried out in a heavily built up urban area in the city of Brno.

The most critical point of PM dispersion modeling is to correctly specify all relevant particle sources. These incorporate primary particulates generated by cars and secondary particulates from long-range transport and street surfaces. Primary PM emission rate released from car exhaust pipes is easy to derive from different studies. Emission production rate from other sources is unclear and must be evaluated by inverse modeling. In this study, PM dispersion from different sources is solved in separate calculations. It enables to estimate PM contributions from urban background, neighboring streets and the studied street canyon.

This study primarily focuses on dispersion of traffic related particulate matter. Two different mathematical approaches were tested with the aim to achieve correct prediction of PM dispersion. Time requirements of the tested approaches were compared too. Namely Eulerian – Lagrangian approach and Passive scalar approach were tested.

NUMERICAL MODEL DESCRIPTION

The 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 0.5 x 0.5 km. The domain includes one long street canyon, Kotlarska Street, with 4 streets that cross the main road, see fig.1.

Traffic in the perpendicular streets is significantly lower compared with the main street. Kotlarska Street is fed by heavy traffic that comes from two intersections located at solution domain borders. Five-story 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).

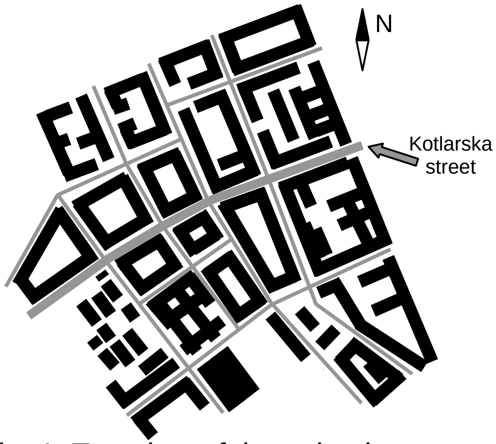


Fig. 1; Top view of the solved area

Fig. 2; View at Kotlarska Street

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-modelled part of the solution domain.

Boundary conditions

Meteorological conditions were set on the model with utilizing of “wind velocity layer” boundary configuration. This boundary configuration prescribes specified wind speed and wind direction at a horizontal layer of air. The air layer is led at height corresponding to the position of measurement. 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. As a model of turbulence, k-ε RNG model was used. To simulate traffic, an original model developed previously by the authors was used (*Jicha et al.*, 2000) that takes into account traffic density, speed of cars and number of traffic lanes.

Mathematical description

CFD code StarCD was used as appropriate tool capable of correct air velocity field prediction in small-scale urban areas. 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 ϕ has the form,

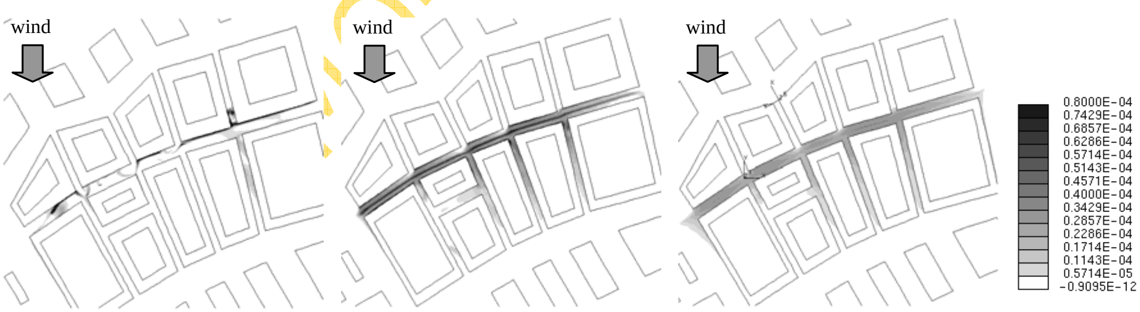
$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i\phi)=\frac{\partial}{\partial x_i}\left(\Gamma\frac{\partial\phi}{\partial x_i}\right)+S_\phi+S_\phi^P . \qquad (1)$$

Variable ϕ stands for velocity components and concentrations. Equation (1) contains an additional source term S_ϕ^P. This term results from the interaction between continuous phase represented by the ambient air and discrete moving objects (cars). In this study authors focus on testing of different options of CFD technique for description of PM dispersion processes. Different mathematical approaches were tested with the aim to achieve correct prediction of PM dispersion. Eulerian – Lagrangian approach to particulate dynamics was tested and compared with an approach based on the substitution of particulate matter by a standard passive scalar.

Eulerian–Lagrangian approach takes into account interaction between air and particulate matter. The air velocity field influences the actual motion of airborne particles. Influence depends on aerodynamic characteristic of the particles and relative motion in the air. In this study the shape of the airborne particles was assumed spherical with the diameter 10μm. Particles density was set to 300kg/m^3. It is necessary to trace trajectories of all included particles during the computational process. This process reduces computational speed and the resulting file becomes significantly larger. Eulerian – Lagrangian approach enables a detail description of particle interaction with walls and other obstacles. The interaction can be solved either as particle stick or rebound. All results presented in this paper were obtained assuming an ideal wall rebound. *Passive scalar approach* utilizes the predicted air velocity field in which the passive scalar is dispersed from specified sources by advection and diffusion. Physical parameters of the passive scalar are assumed the same as for the ambient air. This approach doesn't take into account the real interaction between air and particles. The main advantage of this approach is in simple and fast calculations.

RESULTS AND DISCUSSION

Basic experimental data set was obtained from an in-situ measurements carried out during intensive traffic hours of four working days in November 2004. Information about meteorological conditions, traffic related parameters and pedestrian level PM10 concentrations were collected. PM10 concentrations were measured in nine different positions along Kotlarska Street, 1.5m above the ground surface. Day-averaged values of meteorological parameters and traffic parameters were used for setting up of the numerical model. In the numerical model, a line source of PM was prescribed in the middle of the studied street canyon, 0.1m above the road surface. Mass flux of PM10 particles leaving car tail pipes was evaluated as 2.18×10^{-5} kg/m.s, regarding traffic rate and car speed. Other particles production related with the car movement was evaluated as 3.09×10^{-5} kg/m.s. The sum of both sources was used as line source PM mass flux for the following calculations. We solved the same situations by both above-mentioned approaches.



a) Without inclusion of traffic dynamic | b) Traffic dynamic and Eulerian-Lagrangian approach | c) Traffic dynamic and passive scalar approach

Fig. 3; Predicted PM10 concentration fields at pedestrian level

Pedestrian level concentration field obtained from the calculations is shown for the north wind direction in fig.3. This concentration field was obtained for a) situation without inclusion of traffic dynamic, b) with inclusion of traffic dynamic and the Eulerian-Lagrangian approach, c) with inclusion of traffic dynamic and the passive scalar approach. Fig.3 shows a strong influence of traffic dynamic on PM dispersion process. Concentration fields obtained with the inclusion of traffic dynamic are similar for both tested approaches. The figure 4 shows day averaged PM10 concentrations predicted in different positions and obtained for different meteorological condition. Eulerian-Lagrangian approach provides generally slightly higher PM concentration values in comparison with the passive scalar approach.

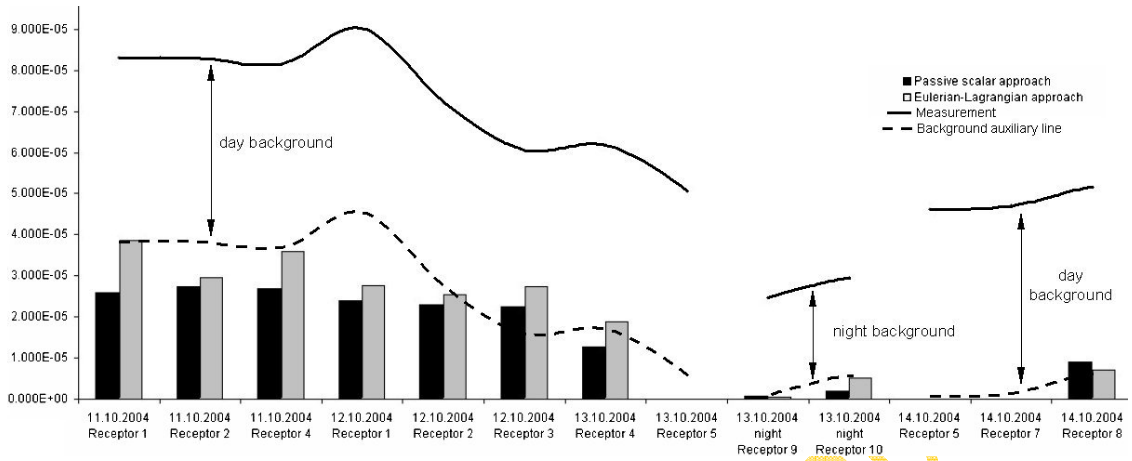
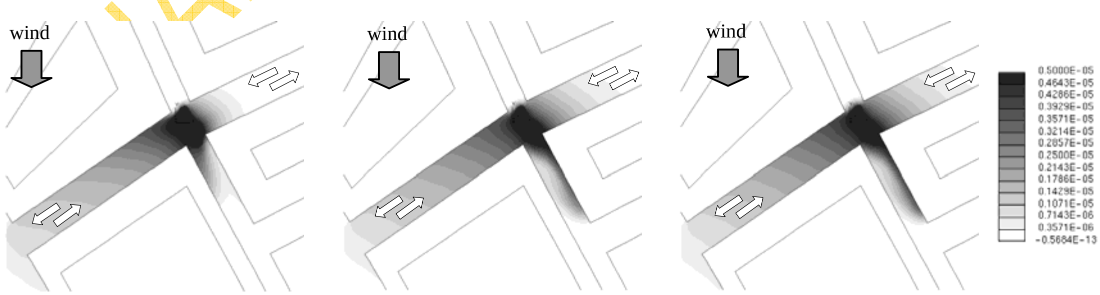


Fig. 4; Comparison of measured and predicted PM10 concentrations

Predictions in fig.4 represent PM induced only by transport in the studied canyon. Local background concentration must be added to the predicted concentrations to reach final measured PM concentration, see fig.4. This is a typical application of an inverse modeling. We obtained different values of the local background concentration for day and night situations. The day local background PM10 concentrations are 44μg/m^3 and the night local background PM10 concentrations are 23μg/m^3. It represents cca 50% of the total day PM10 concentrations and cca 80% of the total night PM10 concentrations. The local background concentrations are the sum of urban background concentrations and local intensive sources of PM located at close vicinity. Two large intersections controlled by traffic lights are the only local sources in the studied area. Other calculations evaluate their contribution to the local background concentrations. The line PM source was switched off and only sources of PM were set at the large intersections. Calculation was carried out for same meteorological condition as before and with inclusion of traffic dynamic. Fig. 5 shows a close look at PM10 concentration field obtained for car speed of 40, 80 and 100 km/h at the vicinity of one intersection. Faster cars intensify the dispersion process and particles reach more distant locations.



a) 40 km/h b) 80 km/h c) 100 km/h

Fig. 5; Influence of car speed on PM10 concentration field in vicinity of the large intersection

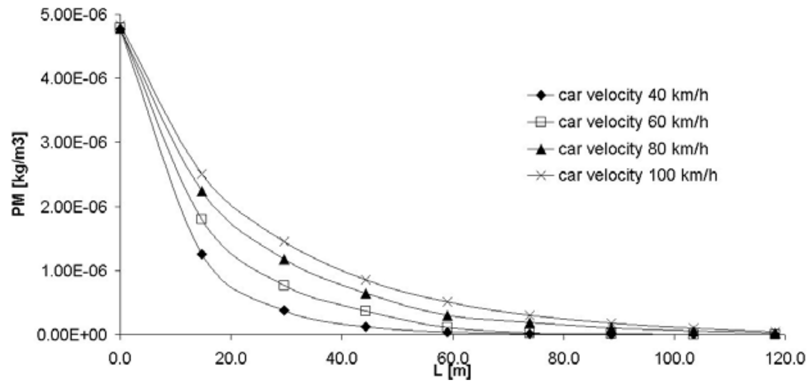


Fig. 6; Relation between PM10 concentrations and distance from the intersection

Figure 6 shows a relation between PM10 concentration and the distance from the intersection. Influence of large city intersections is important in continuous street canyons without gaps between individual buildings. Interruption of street canyon continuity by crossing streets enables "washing out" of the canyon. Intensity of washing out process depends on the wind direction and the local geometry of the area. Results in fig.6 were obtained for a nearly perpendicular wind direction to the street canyon and the first interruption at the distance 120 m from the large intersection. We can see that the influence of the local source is generally limited by the first street canyon interruption for this wind direction.

CONCLUSIONS

In this paper authors present different ways of PM dispersion modeling in an urban area. The CFD code StarCD was used as an appropriate numerical tool. The study focuses on dispersion of particulate matter originating from traffic in the studied street canyon. A method developed for traffic-induced flow (Jicha at al., 2000) was applied for a correct inclusion of the traffic influence. Obtained results show a significant influence of traffic dynamic on the final PM concentration field. Two approaches of PM dispersion were tested and compared. Eulerian – Lagrangian approach seems to be more realistic and enables a more accurate description of the interaction between the continuous phase and particles. Passive scalar approach uses more simplifications but calculations are faster in comparison with Eulerian – Lagrangian approach. Inverse modeling was used to determine local PM background concentrations. The local background PM concentrations represent approximately 50% of the total day PM10 concentrations and approximately 80% of the total night PM10 concentrations. The influence of car velocity on PM dispersion from local sources was also tested. The influence of large city intersections is important in continuous street canyons without gaps between individual buildings. This influence is generally limited by first interruption of street canyon continuity.

ACKNOWLEDGEMENT

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