Air Pollution Dispersion in Segments of Urban Areas

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Abstract: - The paper presents results of numerical calculation of pollutants dispersion in segments of urban areas. Geometry of the typical segments of urban area was transformed in numerical models built up from hexagonal finite elements. The solution domains represent areas of 1 × 1 km. Traffic is considered as the primary source of airborne particles. Dispersion of pollutants from the traffic path in direction perpendicular to the traffic path is monitored as important parameter for subsequent simplified prediction of air pollution concentration in urban areas. Deposition of particles is described by inclusion of Brownian diffusivity and eddy diffusivity in close vicinity of the surfaces. The relation of PM10 concentration and perpendicular distance from the line source was used for evaluation of the PM10 dispersion intensity. Numerical modelling (CFD code StarCD) was used as the computational code for carried out studies. The Eulerian approach of the particle dispersion was engaged. The parametrical study was focused on assessment of pollutant dispersion from line sources surrounded by the buildings with various configurations.

Key-Words: - particulate matter, CFD modelling, dispersion, particulate matter, line source

1 Introduction

Many urban areas are often heavily polluted by airborne particles released by road traffic from transit traffic paths. These traffic paths frequently represent major line sources of air pollution in urban areas. The highest concentrations of PM are generally present at a close vicinity of major traffic paths. Lower concentration of PM is identified in bigger distance from the major traffic path. Many different parameters influence formation, transport and deposition of particles at these locations. Particulate matter consists from complex mixture of motor vehicle exhaust particles, tire dust, brake lining wear dust, soil dust and other materials. The particles behavior is influenced by transportation in moving air, settling due to the gravitational acceleration, interaction with buildings walls, deposition on 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. Appropriate simplifications must be used for correct and fast mathematical evaluation of PM concentration on small-size urban areas.

Particles spend a long time in urban areas and travel through long distances. Numerical models are necessary for a detail prediction of PM concentrations in close vicinity of traffic paths. Dispersion of particles is directly connected with the geometry of urban areas and traffic conditions. Different geometry of buildings in the surrounding of the traffic path was engaged in separate models. Moving vehicles enhance mixing processes in their surroundings. Mathematical description was used for inclusion of moving care influence on dispersion processes just above the road surface. Small scale models based on the CFD technique represent a convenient tool capable to involve the above mentioned parameters with better accuracy then analytic and statistical models. Numerical modelling (CFD code StarCD) was used as the convenient computational code for carried out studies.

The Eulerian approach of particle dispersion modelling was engaged [2]. The parametrical study was focused on assessment of PM10 dispersion from line source surrounded by the buildings with various configurations. The relation of PM10 concentration and the perpendicular distance from the line source is used for evaluation of the PM10 mass flux oriented perpendicularly to the line source. Actual size and density of particles are taken into account.

The paper focuses on creating an operative system that evaluates the exposure of local population to imission in small settlements. A catalogue of concentration maps of selected model areas of small settlements is designed for a fast evaluation.

2 Transport of pollutant in urban areas

A catalogue of concentration maps of selected model areas of small settlements is designed for a fast evaluation.

Figure 1 Illustrative example of a small settlement

Urban areas significantly influence the flow of the air in the canopy layer. Specific configurations of buildings and roads create complex conditions for dispersion of pollutants generated by road transport. The cars affect the current velocity field of air above the ground. The presence of turbulent eddies affects both the velocity field of air and inherent dispersion of pollutants.

Street canyon

Traffic path with two-way traffic closed by buildings on both sides creates so call a street canyon. The wind blowing over the building roofs in direction perpendicular to street canyon axis forms transverse vortex that carries the emissions produced by cars to the leeward wall of the street canyon [7]. Emissions are moved up along the leeward facade of buildings and transported to air layer above the rooftops. Cars in the street canyon affect the speed of rotation of the cross vortex [3]. Stationary vehicle creates a physical barrier to flow. In addition, a moving cars generate turbulent eddies. Turbulent eddies then slow down transverse vortex in the street canyon. Intensive mixing of air in the street with counter operation causes rapid dispersion of pollutants and significant reduction of local maxima of air pollution concentrations.

Roads intersection

Large intersections represent an intensive point source of traffic related pollution generated in urban areas. Influence of large city intersections is very important in continuous street canyons without gaps between individual buildings. Intensity of washing out process depends on the wind direction and the local geometry of the area. Results in Fig. 2 were obtained for a 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. The higher car velocity causes higher PM10 concentrations in the street canyon.

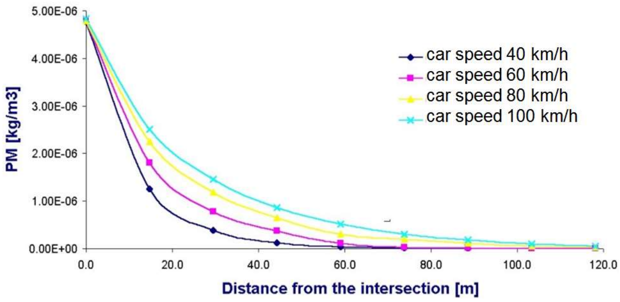

Figure 2 Relation between traffic generated PM10 concentrations and distance from the intersection for variety of tested car speeds

3 Classification strategy for model areas of small settlements

The selection of model areas of small settlements was performed with the aim to prepare numerical models of selected areas which represent typical configurations of buildings and emission sources in small settlements. The selected model areas are used for calculating concentration maps of air pollution. The obtained results should be representative and usable for evaluations of a large number of small settlements of a similar layout.

In the first step when selecting model areas, the attention was paid to the character of urban layout in relation to the main road. Small settlements were classified as follows in this step:

- bordering a transit road,
- run through by a transit road.

An extensive study of aerial views of small settlements helped us to select two characteristic shapes of transit roads which frequently appear in small settlements:

- direct road,
- road with a change in direction by 90°.

Another feature of the selected model areas was the shape of built-in areas. In this respect, the characteristic model areas of small settlements were divided into three groups:

- solitary standing family houses forming a settlement,
- continuous row of buildings surrounding the main road and other solitary structures,

- urban character of a small settlement with street canyons in its central part.

4 Model of pollutants dispersion and related boundary conditions

CFD (computational flow dynamics) method was used for the creation of concentration maps of pollutants. This method allows including a detailed description of the geometry of an area and the dispersion of pollutants on computed 3D air velocity field. Euler method was used as a suitable approach to deal with the pollutant dispersion. This method is based on a numerical approach to the system of differential equations accurately describing air flow, transport of gaseous pollutants and small suspended particles. The solution can be steady as well as transient. The correctness of the calculated air velocity field depends on the quality of the assigned geometry of an area and assigned boundary conditions. There is no fundamental limitation thus when dealing with urban areas the calculation can include detailed geometry of individual buildings. The information on the concentration of pollutants is collected in nodal points of the control volumes. Calculation is based on the balance equations for conservation of matter, energy and momentum, which describe the transfer between individual volume elements of the numerical model. The size reduction of the used volume elements increases the accuracy of results but significantly increases hardware requirements and computational time. This fact requires a careful decision of the size of the area in question and of the size of the used volume elements.

The dispersion of pollutants is critically influenced by the existing air velocity field. The air field in a given area is formed by the effects of the assigned wind, geometry of buildings, and the effect of moving vehicles near roads. The impact of vehicles is crucial in most cases when dealing with the area in close vicinity of the road [5]. The movement of vehicles is significant for dispersion of pollutants, ispecially in situations when the natural advection is insufficient (e.g. in windless conditions). The inclusion of moving vehicles in the calculation is performed in two steps:

- inclusion of force effects of vehicle on air,
- inclusion of production of the kinetic energy of turbulence.

The force effects of the air on moving vehicles are described by the resistance force [4].

The reaction to the aerodynamic resistance force is the force that the vehicle pushes the fluid. This effect is included in the numerical solution in the form of the volume force active at control volumes where vehicles drive through.

The created detail mathematical model always represents only a part of the real area. The size of the model itself is limited by the amount of time for processing and by the hardware. The limitations due to the model size lead to necessary use of convenient boundary conditions which accurately substitute the influence of the surroundings. The boundary condition "slip wall" is used for the upper border of the computation area. The boundary condition assigned to side walls must allow prescribing the wind velocity profile above the terrain corresponding with real conditions in the lower atmospheric level. This approach allows to include the effect of the surrounding environment at the place of the area border. The mathematical expression of the wind velocity profile is

$$u = u_{ref}\left(\frac{z}{z_{ref}}\right)^{a} , \tag{1}$$

where, u … wind velocity in height z,
u_{ref} ... wind velocity in reference height,
z … elevation coordinate,
z_{ref} … reference height,
a … velocity profile coefficient.

Influence of vegetation and small obstacles is involved in calculation as corresponding parametric roughness prescribed on ground surface.

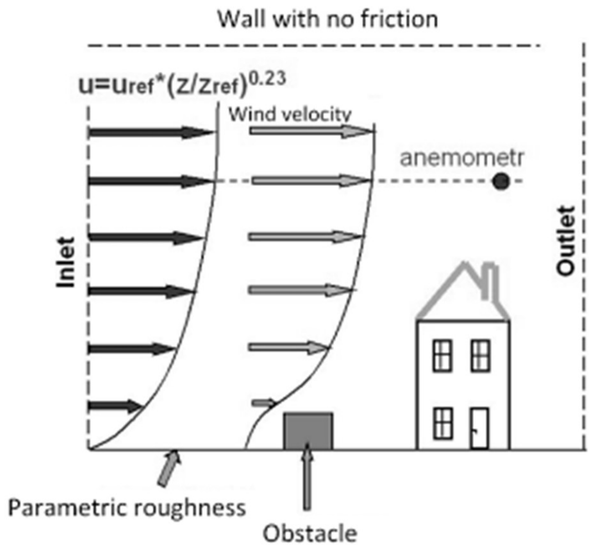

Figure 3 Wind velocity profile assigned to the side wall of numerical model

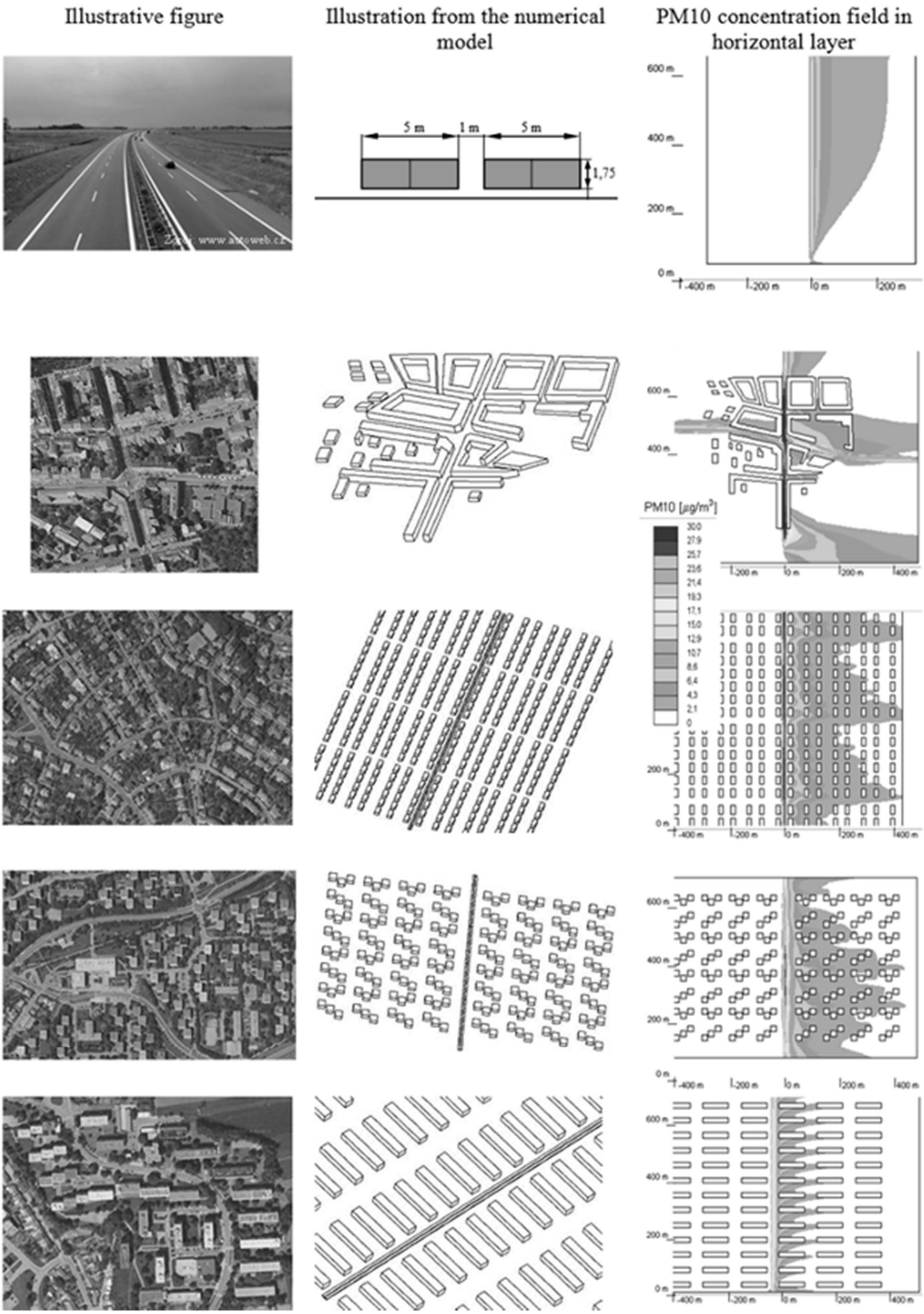

Figure 4 The studied urban configurations and obtained PM10 concentration fields at height 1.5 m above the ground

5 Mathematical description

The 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

$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i\phi)=\frac{\partial}{\partial x_i}\left(\Gamma\frac{\partial\phi}{\partial x_i}\right)+S_\phi, \quad (2)$$

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 k-ε RNG model of turbulence [9] was used.
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 [1]

$$F=K\frac{dC}{dz}+v_s C \quad . \quad (3)$$

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 ground boundary layers [6]. Close to the ground, 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 [8]

$$v_s=\frac{D_p^2\rho_p g C_c}{18\mu} \quad (4)$$

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 [8]

$$C_c=1+\frac{2\lambda}{d_p}\left[1.257+0.4\exp\left(-\frac{1.1d_p}{2\lambda}\right)\right], \quad (5)$$

where λ is the mean free path of gas molecules.

It is impossible to accurately quantify production of all actual PM sources. Therefore, an appropriate simplification of particles production description is convenient for a numerical solution of PM concentration field.

The primary exhaust emission factor is determined for car fleet composition – diesel engines to petrol engines = 1 to 3. The primary exhaust emission factor is calculated as

$$S_{pe}^{r}=0.75\times f_{PM10}^{B}+0.25\times f_{PM10}^{D}\ , \quad (6)$$

where f_{PM10}^{B} is the PM10 emission factor of petrol engines and f_{PM10}^{D} is the PM10 emission factor of diesel engines derived for a horizontal road. The particular emission factor values were derived from software MEFA v.02 (Mobile Emission Factors) published by the Ministry of Environment of the Czech Republic. The PM10 primary exhaust emission factor value was calculated as 0.0179 g/km car.

A non-exhaust particle source related with traffic involves the primary and the secondary particles. The primary non-exhaust particles are released from cars, tires and road surfaces. The emission factors of non-exhaust particles released from cars and tires can be easily derived from different studies. Amount of the primary road surface particles is a function of a road surface material and an actual road state. Non-exhaust secondary particles are silt road particles drawn up from road surface. The re-suspension process intensity is fully dependent on an actual road silt load. The total PM10 emission factor is a sum of the exhaust particles emission factor and the non-exhaust emission factors. The average total PM emission factor of the model domain was derived from a previous study as 0.06265 g/km car.

The average total PM emission factor serves for the determination of the only particles source term prescribed in the numerical model. The source term was assigned at the air layer close to the ground surface, where major quantity of airborne particles is generated.

6 Result of calculations

The parametrical study was carried out for five different urban configurations the straight traffic path with inclusion of cars movement, namely:

- traffic path in flat area without buildings,
- traffic path in system of perpendicular street canyons,
- traffic path in regular configuration of discrete residences,
- traffic path in regular configuration of small blocks of flats,

• traffic path in regular configuration of big blocks of flats.

The car velocity 50 km/hour and traffic intensity 720 cars/hour (in each direction) were considered in all tested cases. The geometry of the studied urban areas is shown in Fig. 4. The spherical particles with diameter 10 micrometres and density 1200 kg/m^3 were released just above the road surface.

Wind velocity was set 2 m/s or 4 m/s in direction perpendicular to the traffic path. Particle dispersion

was solved with utilizing of the Eulerian approach and inclusion of particle deposition on the ground surface.

The Fig. 4 shows PM10 concentration fields obtained for different configuration of buildings geometry. The first example presents PM10 dispersion from the traffic path in flat opened area without any buildings or obstacles. In this case, particles are dispersed uniformly in air layer above the ground. The higher air velocity causes more intensive dispersion of particles in bigger quantity of fresh air.

The concentration fields were collect into a database of concentration maps, see Fig. 5 , so that the calculated concentration fields would not stay only as a content of continuous reports. This database can be a tool for a quick orientation in results and a practical tool for the evaluation of similar areas.

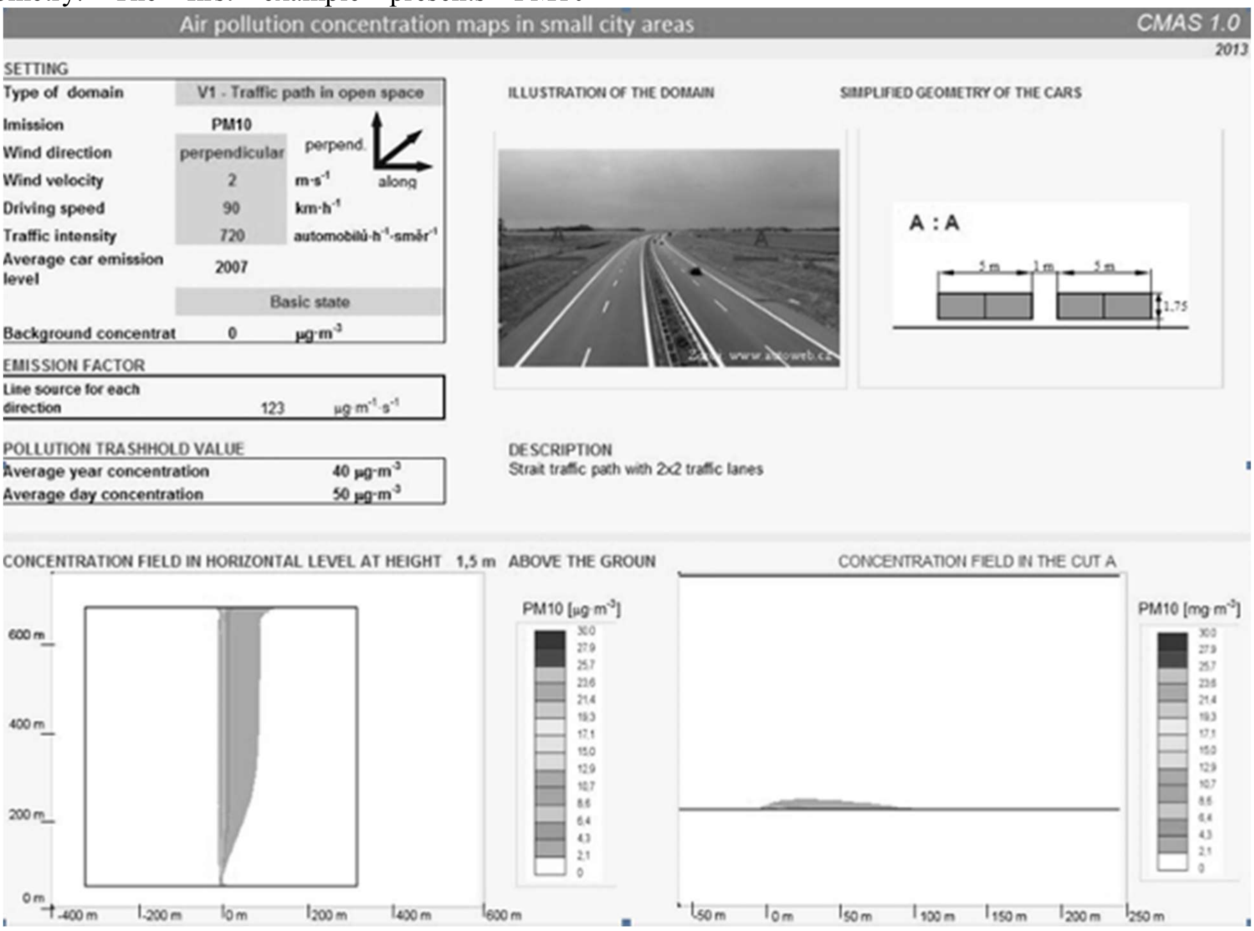

Figure 5 Example of the graphic interface of the concentration map database

The database is an interactive tool allowing a quick search for corresponding situations and displaying of reached results, which can help to users to evaluate the imission burden of similar settlements. Taking into account the fact that in the close vicinity of emission sources and in urban areas “under building roofs” it is impossible to use common recommended dispersion models, the database represents the only option to quickly evaluate local areas along roads while considering the specific geometry of buildings and traffic characteristics.

The database collects outputs of calculations which are expected for further use. Each inserted concentration field is identified with a description of the geometry of building, description of corresponding meteorological conditions (wind velocity and direction), traffic parameters (driving speed, traffic intensity), basic average emission level of vehicles, and background concentration.

One particular solution domain will be investigated in this paper as example of numerous calculations. The studied street canyon is located at the centre of the city of Brno (population 350000). Five-story buildings (20 m high) form both sides of the street canyon. Width of the street is 22 m. Two-way traffic in total four traffic lanes is present in the street. The day highest traffic rate is 1530 cars/hour.

In-situ measurements were carried out during peak traffic hours. It is necessary to regard the actual traffic activity for a following comparison of the prediction and the measurements. The peak traffic activity was assessed as 1.8× the daily average traffic activity. The peak traffic contribution concentration was calculated as 8.5 $\mu g/m^3$. The local background PM10 concentration was derived from a measurement outside of the urban area as 15 μg/m3. The local PM10 background concentration value 45 $\mu g/m^3$ were obtained in central part of the city of Brno.

The total predicted PM10 concentration is calculated as sum of the predicted concentration and the regional background concentration.

The result of this calculation is 23.5 $\mu g/m^3$ for outskirts areas. For local models located in central part of the big city, we obtained total PM10 concentration 53,5 $\mu g/m^3$ in close vicinity of main traffic path.

In comparison with long time measurement, the result shows that the predicted concentration values underestimate the measured concentration values in close vicinity of traffic path. The difference is probably due to an intensive re-suspension of soil particles. This process is not taken into account in the numerical models due to difficult description of its source term.

Figure 6 The local solution domain for experimental verification

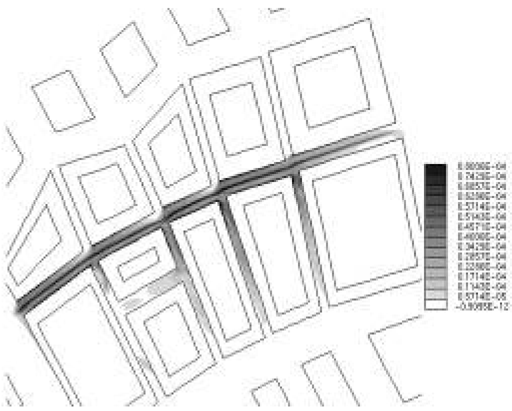

Figure 7 Predicted PM10 concentration fields at height 1.5 m above the road surface, north wind direction, wind velocity 2 m/s

The predicted concentrations were compared with measured concentrations at nine receptor points located in the main street canyon and its close surrounding. For the north wind direction, the local background PM10 concentration was assumed 45 μg/m3. The predicted concentration contribution from traffic is 27.5 μg/m3. Then, the total predicted PM10 concentration is 72.5 μg/m3. The corresponding concentration obtained from measurement is 83 μg/m3. At this case, the result of calculation represents 87.4% of the concentration value obtained from the measurement. The local numerical model underestimates the total PM10 concentrations.

The set of calculations was carried out on the numerical model of the studied area. During the calculations, the traffic rate was changed step-by-step from the day highest value to the situation without traffic. All other parameters remained unchanged were changeless. Predicted PM10 concentrations were evaluated in 9 receptor points located in the studied street and perpendicular side-streets.

The Figure 8 shows graphical expression of obtained results. Higher traffic rate causes higher PM10 concentrations in all considered receptor points. But, the relation between traffic rate and PM10 concentration is not strictly linear. Increasing traffic causes a more intensive transport of particulate matter from the line source, located in the middle of the studied street canyon, to the positions of the receptor points. This behavior is influenced by the actual value of kinetic energy of turbulence in the vicinity of the line source. Higher traffic rate causes higher value of kinetic energy of turbulence above a road surface. Intensive mixing of air intensifies transport of PM in the perpendicular direction to the street. That results in the presented progressive increase of PM concentrations with increasing traffic.

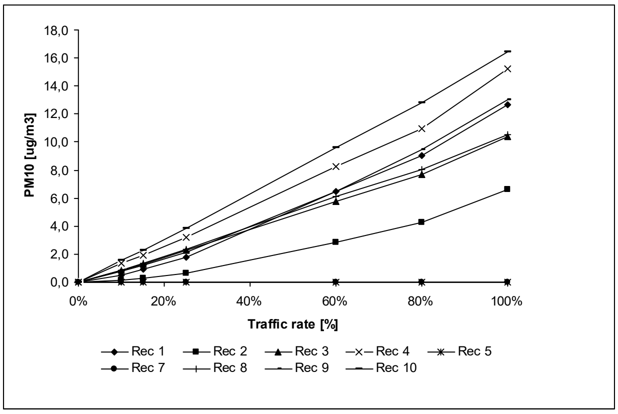

Figure 8 Relation between traffic rate and PM10 concentrations (1530 rs/hour = 100%)

7 Conclusion

Particular geometry of buildings directly influences the air velocity field in the ground surface and subsequently the PM10 concentrations field. The significant pollutant concentration "tongues" are formed in the gaps between buildings. These concentration tongues are characterized significantly higher PM10 concentration in comparison with surrounding.

Some results can be formed based on comparison of the PM10 dispersion from the line source in urban areas and nonurban area. Buildings generally enhance the dispersion process by forming complex air field in the ground surface. The PM10 mass flax is enhanced in vertical direction by convenient orientation of buildings. The PM10 concentration at areas with the major concentration "tongues" is up to twice higher than PM10 concentration identified in nonurban configuration at same distance from the line source.

The predicted PM10 concentration fields were compared with the results of measurement. The tested numerical models underestimate the terminal PM10 concentration values. The predicted results represents 87.4 % of the measured PM10 concentration. The difference is probably due to an intensive re-suspension of soil particles. This process is not taken into account in the presented numerical models due to a difficult description of its source term.

Another step of the research has to be focused on more detailed description of turbulent diffusion in the vicinity of moving cars.

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