Numerical simulation of air circulation and pollution transfer in urban conditions with explicit accounting for the landscape

V.A. Shlychkov,[1] A.I. Borodulin,[2] and B.M. Desyatkov[2]

[1]*Institute for Water and Environmental Problems, Siberian Branch of the Russian Academy of Sciences, Novosibirsk*
[2]*Institute of Aerobiology of the State Research Center of Virology and Biotechnology "Vector," Koltsovo, Novosibirsk Region*

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Structure of urban airflows is complicated and strongly depends on meteorological conditions, topography, arrangement and height of urban buildings and constructions. The most dangerous environmental situations are realized in the presence of the stable air stratification and weak wind. The hydrodynamic model with flow characteristics averaged over the height of the ground atmospheric layer has been formulated taking into account the detailed local air circulation and resolution of individual buildings and constructions. Calculations of air pollution propagation are illustrated by the example of Koltsovo district, Novosibirsk Region.

Determination of air pollution concentration fields over large cities with the use of models accounting for resolution of individual buildings and constructions is a very cumbersome and time-consuming problem. Often it is necessary to determine such fields for only a part of the considered territory, for instance, one of the districts of a city. To our opinion, it is reasonable in this case, to apply first some simplified model for calculations of contaminant concentration fields over the whole city. Then the obtained data can be used as initial and boundary conditions for more detailed calculations accounting for individual urban buildings and constructions. An example of such solution is considered in this paper.

Not far from the Koltsovo settlement (about 2 km apart), a poultry-farm is situated (Fig. 1*a*). When wind blows from the farm toward Koltsovo, its habitants feel a specific smell causing some discomfort.

The problem of weightless contaminant propagation from the poultry-farm to the Koltsovo territory was solved at the first stage with the use of the model of air contaminant propagation involving numerical methods for determining fields of wind speed, air temperature, and humidity.[1] In the calculations, buildings and constructions were accounted for integrally through setting roughness parameters of the underlying surface. A two-dimensional surface source of a vertical contaminant flow, uniformly distributed over the farm territory, was specified. Meteorological conditions, typical for June nights (a stable stratification and a weak wind directed from the poultry-farm toward Koltsovo) were simulated. Calculations were carried out for an area of 4×4 km with a 40×40-node grid. Results are exemplified in Fig. 1*b*, where arrows show the vector field of wind speed and isolines – the contaminant concentration cross section at a height of 2 m above the ground.

Consider the second stage of the problem solution. The wind regime over the terrain is formed by the external flow, turbulent mixing, and local topography; it is also determined by the temperature stratification of air masses. In conditions of unstable stratification in summer time caused by a strong heating of the underlying surface, there appear strong vertical flows in atmosphere transporting the near-ground matters into upper atmospheric layers.[2]

In conditions of stable stratification, two layers with different properties are formed during the near-ground air movement. The bottom layer, adjacent the ground, is strongly turbulized because of the surface roughness and the vertical wind speed gradient. This is a so-called ground quasistationary sublayer, where vertical turbulent flows are constant over height. The ground layer thickness depends on the underlying surface type and wind magnitude, which makes several tens of meters at a stable stratification. As a rule, the propagation of contaminants from ground sources takes place just within this layer.

Above this layer, a weakly turbulized atmospheric boundary layer is situated formed by daily variations of the underlying surface temperature. The vertical gradients of wind speed fields there are weaker than in the ground layer. The layer, stipulated by daily variation of meteorological conditions, is separated from the upper free atmosphere by an inversion sublayer. Hence, the flowing around relief irregularities in conditions of stable stratification corresponds to motion of a heavy liquid below an easier one.

Introduce the Cartesian coordinates x_i, $i = \overline{1,3}$, where axis x_3 is directed vertically and horizontal axes x_1 and x_2 are directed along boundaries of the Koltsovo district (Fig. 1*a*). Define the solution region as a parallelepiped, the bottom boundary of which coincides with the underlying surface:

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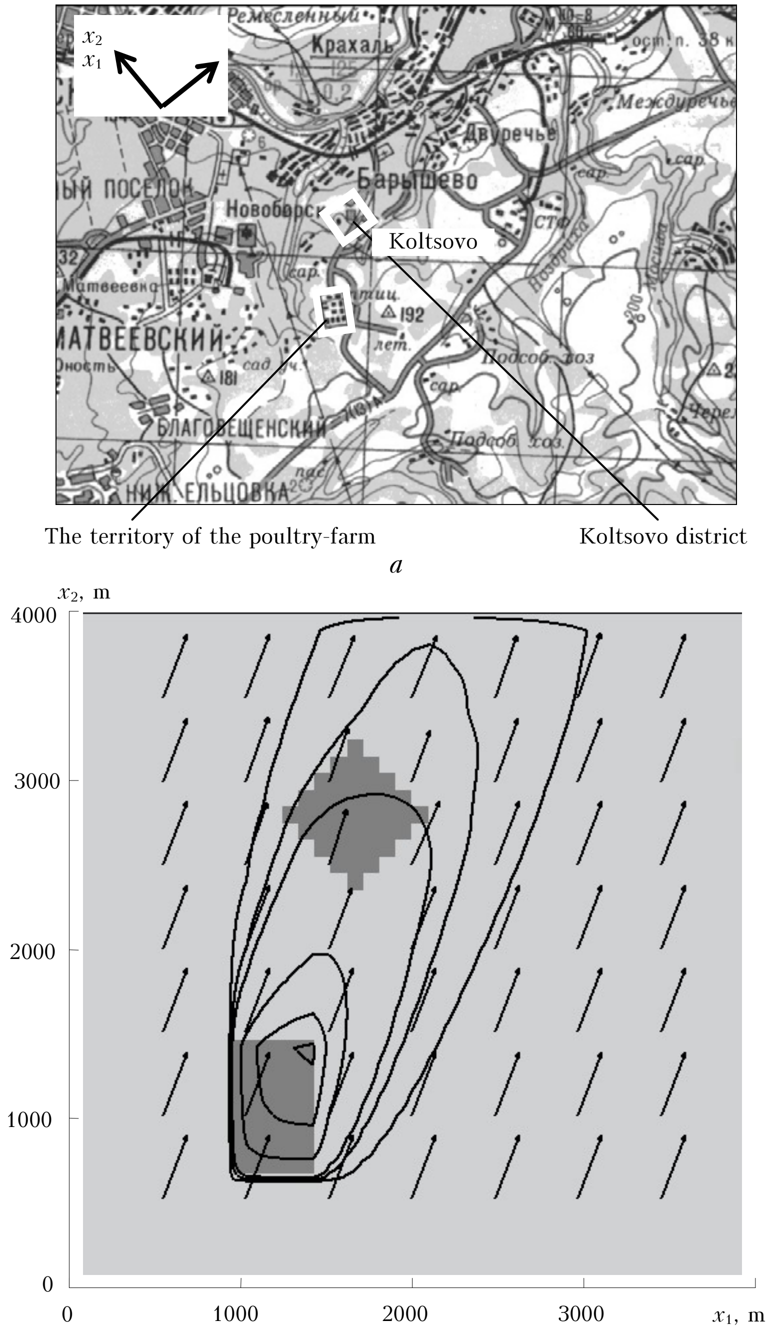

Fig. 1. The fragment of the region topographical map (*a*) and the example of calculation of the fields of wind speed and contaminant concentration cross section at a height of 2 m above the underlying surface (*b*).

$$0 \le x_1 \le L_1;\ 0 \le x_2 \le L_2;\ \delta \le x_3 \le h,$$

where L_j $(j = \overline{1,2})$ are horizontal sizes of the region; $\delta(x_1, x_2)$ determines the terrain topography, and h is the coordinate of the top boundary. If to take hydrodynamic equations of incompressible liquid[3] as initial ones, then at characteristic horizontal scales of the processes $L_1 \approx L_2$ can be considered much greater than h. This supposition allows us to accept the quasistatics hypothesis and simplify the hydrothermodynamic equations by averaging over vertical[4]:

$$\frac{\partial h U_1}{\partial t} + \frac{\partial h U_1^2}{\partial x_1} + \frac{\partial h U_1 U_2}{\partial x_2} =$$

$$= -\lambda\, \Delta T h \frac{\partial (h+\delta)}{\partial x_1} + \frac{\partial}{\partial x_1} hK \frac{\partial U_1}{\partial x_1} + \frac{\partial}{\partial x_2} hK \frac{\partial U_1}{\partial x_2} - c_{\mathrm{d}} |U| U_1;$$

$$\frac{\partial h U_2}{\partial t} + \frac{\partial h U_1 U_2}{\partial x_1} + \frac{\partial h U_2^2}{\partial x_2} =$$

$$= -\lambda \Delta T h \frac{\partial (h+\delta)}{\partial x_2} + \frac{\partial}{\partial x_1} hK \frac{\partial U_2}{\partial x_1} + \frac{\partial}{\partial x_2} hK \frac{\partial U_2}{\partial x_2} - c_{\mathrm{d}} |U| U_2;$$

$$\frac{\partial h}{\partial t}+\frac{\partial hU_1}{\partial x_1}+\frac{\partial hU_2}{\partial x_2}=0,$$

where U_j $(j=\overline{1,2})$ are expectancies of horizontal wind speed components averaged in the layer $\delta \le x_3 \le h$; K is the turbulent exchange coefficient; $\Delta T > 0$ is the vertical temperature fall between the stable ground layer and the above atmosphere; λ is the floating parameter; $|U|=\sqrt{U_1^2+U_2^2}$, and c_d is the coefficient of resistance. Thus, to determine U_j and h, calculation of spatial-temporal distribution of meteorological fields is reduced to solving the above-described set of equations.

Let us set edge conditions at side boundaries in the form

$$U_1=U_{01};\ U_2=U_{02};\ h=h_0 \text{ at } (x_1,x_2)\in\Gamma^+;$$

$$\frac{\partial U_1}{\partial x_1}=\frac{\partial U_1}{\partial x_2}=\frac{\partial U_2}{\partial x_1}=\frac{\partial U_2}{\partial x_2}=0 \text{ at } (x_1,x_2)\in\Gamma^-,$$

where Γ^+ is the locality of air flowing into the region and Γ^- is the locality of air flowing out. Define $U_j = U_{0j}$ and $h = h_0$ as initial conditions.

The turbulent closure is carried out on the base of a two-dimensional model[5]:

$$K=\alpha_s \Delta x_1 \Delta x_2 \sqrt{D_T^2+D_S^2},$$

where

$$D_T=\frac{\partial U_1}{\partial x_1}-\frac{\partial U_2}{\partial x_2};\ D_S=\frac{\partial U_2}{\partial x_1}+\frac{\partial U_1}{\partial x_2};$$

$\alpha_s \approx 1$ is the constant, Δx_1 and Δx_2 are intervals of the difference grid.

The "flat" evolution model for the concentration field $C(x_1, x_2, t)$ also can be obtained through vertical averaging of the transport equation and diffusion of a weightless passive contaminant[6]:

$$\frac{\partial hC}{\partial t}+\frac{\partial hU_1C}{\partial x_1}+\frac{\partial hU_2C}{\partial x_2}=\alpha_c\left(\frac{\partial}{\partial x_1}hK\frac{\partial C}{\partial x_1}+\frac{\partial}{\partial x_2}hK\frac{\partial C}{\partial x_2}\right),$$

where C is the expectancy of contaminant concentration averaged in the layer $\delta \le x_3 \le h$. Define the edge conditions as

$$C=C_0 \text{ at } (x_1,x_2)\in\Gamma^+;$$

$$\frac{\partial C}{\partial x_1}=\frac{\partial C}{\partial x_2}=0 \text{ at } (x_1,x_2)\in\Gamma^-.$$

Solution procedures for the above equations are based on the finite-difference approximation of the initial systems using a calculation pattern. The rectangular grid with nodes spaced over bounds of an elementary three-dimensional cell is used. Grids of such type allow conservative difference schemes to be built; the use of implicit methods provides for stability of the method at the numerical integration. The spatial approximation of differential operators is based on recent ideas of monotonic schemes and on TVD technique. In particular, this provides for nonnegativity of *a fortiori* positive variables. The class of implicit schemes of high-order approximation[7] is used in numerical algorithms.

Let us consider calculation results. The Koltsovo district is characterized by dwelling multistorey buildings and few-storied administrative buildings (Fig. 2). A grid of 140×130 nodes with a 5 m step in both directions x_1 and x_2 was applied in calculations for an area of 700×650 m. The difference in heights of the terrain did not exceed 10 m. The building arrangement and relief were set through the function $\delta(x_1, x_2)$.

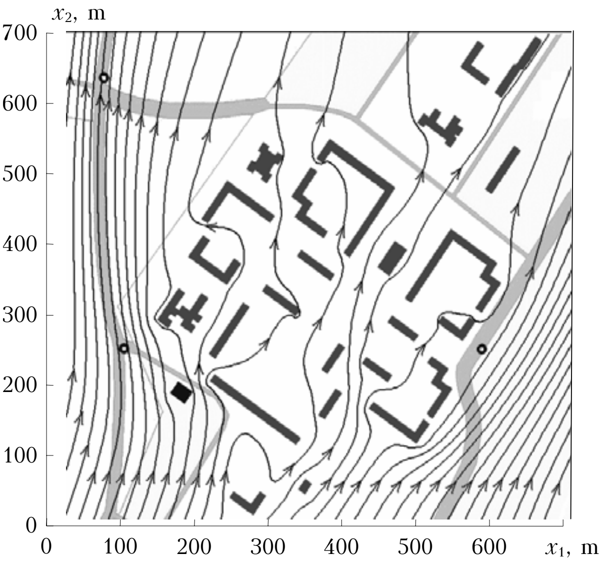

Fig. 2. Isolines of current function in the Koltsovo district in conditions of a strongly stable stratification.

At the second stage of calculations, the detailing of fields earlier obtained on the coarse grid was carried out by means of grid refinement and direct description of the topography and buildings using the above set of equations. The speed and concentration values at side boundaries of the region of flowing in were set based on results obtained on the coarse grid.

The nonstationarity effect weakly manifests itself on the considered scales; processes relax sufficiently quickly (less than for an hour). Therefore, we can consider only a steady flow. Introduce the current function ψ based on relations[8]

$$hU_1=\frac{\partial\psi}{\partial x_2};\ hU_2=-\frac{\partial\psi}{\partial x_1}.$$

Curves in Fig. 2 illustrate the spatial distribution of the current function for the case of strong inversion of the ground layer at $\Delta T = 10°C$ and a weak wind (arrows show directions of particles movement along trajectories). Under these conditions, mechanisms of airflow over building tops are blocked; and only side flow, similar to heavy liquid flow around obstacles, is realized (this is seen from the fact that current lines in Fig. 2 do not intersect building contours).

Note, that on a flat surface the trajectories would be straight lines directed along the external velocity vector.

The increased concentration of current lines at the side (relative to the flow) boundaries of the district is evident of the wind speed increase there. On the contrary, a curve spread is observed at the front side and inside the district accompanied with formation of an irregular structure of current lines, geometry of which is formed under the influence of individual buildings. This witnesses for the flow deceleration on the windward side and inside districts, as well as for formation of the windless zone (wind shadow) behind obstacles. A similar wind shadow is also formed on the leeward side due to the resultant action of the urban agglomeration on the external flow.

The flow deceleration before obstacles results in increase of the moving layer depth h and formation of an air flow lift zone. When h exceeds building heights, air flow passes over obstacle tops. Immediately above the tops, the flow speed jumps and can exceed by several times the speed of the moving flow; at the backsides of buildings it sharply decreases. The combined movement with flowing around and over is observed when external wind is amplified and the inversion decays. Realization of one or another mechanism of the flow-obstacle interaction depends on the local and external dynamic parameters, individual characteristics of the building, its position, and so on.

Features of intrinsic flow dynamics determine regularities of contaminant redistribution over the district territory. Figure 3 shows the normalized calculated field of concentration delivered by an external flow. In calculations, moving flow speed was equal to 4 m/s; the temperature difference is 4°C in a stable layer with the initial height h_0 of 20 m.

As is seen in Fig. 3, the pediment of the building at the southwest boundary of the district serves a screen impeding contaminant propagation inside. Because of the building loftiness (about 30 m) the flow round processes dominate, redirecting the flow to the district periphery. An insignificant impurity concentration is observed backside the building. Southeast buildings are lower (about 15 m). Therefore, flow acceleration there, when flowing over, results in significant impurity concentrations, which 2.5 times exceed the background maximum (see blacked regions in Fig. 3). The concentration decrease behind low obstacles is negligible, which is seen from a small clearance in their leeward traces. Individual contaminant streams propagate inside the district through inter-building spaces under action of dynamical head; however, their contribution to the total pollution is insignificant.

As a whole, due to the building up, the total impurity mass over the district decreases by 40% relative to free-flow transfer over a flat surface. Thus, under the given meteorological conditions, the district is an environmental self-protector, which directs main polluting flows to the periphery. However, it should be noted that there exist dead zones close to building surfaces "meeting" the flows, where contaminants are accumulated.

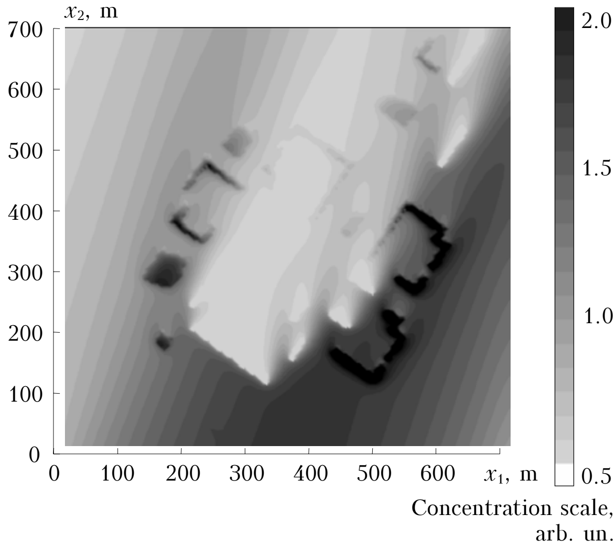

Fig. 3. Calculated normalized concentration field delivered by the external flow.

Thus, the urban building system plays an important role in formation of the pollution field in conditions of a weak wind and inverse stratification, i.e., under conditions adverse for the air quality. The calculations show that a city as a landscape macrostructure causes deformation of external flows and impedes pollutant transfer to internal zones. At the same time, urban agglomerates redistribute the moving flow and weaken local circulations; this makes difficult the efficient airing of the terrain. Anthropogenic pollutants generated inside cities can in these cases severely worsen the environmental situation.

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