Simulation of pollutant distribution near aluminum production plants

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Basic specific substances emitted into the atmosphere by an aluminum production plant are considered. Taking into consideration local climate features, areas of hazardous pollution are simulated from the viewpoint of violation of the accepted standards. The data on the sickness rate among children living in these areas are presented.

Among 1000 towns of the Russian Federation, Shelekhov falls in the list of 45 most polluted towns. In spite of the general tendency to a decrease of emissions (except for nitrogen oxides) (Fig. 1), the annual pollution index still keeps higher than in Irkutsk, Angarsk, and Bratsk and many times exceeds the mean pollution index over Russia. This high pollution level is caused, first of all, by the aluminum production, which is characterized (as all aluminum production plants in Russia) by the low level of utilization of harmful substances, prevalence of self-baking anode technologies, the absence of tight normative control, etc. The situation is significantly complicated by emissions from heat and power plants and heavy traffic, as well as by the fact that control organizations sometimes give permissions for pollutant emissions several times exceeding the maximum permissible level for many ingredients.

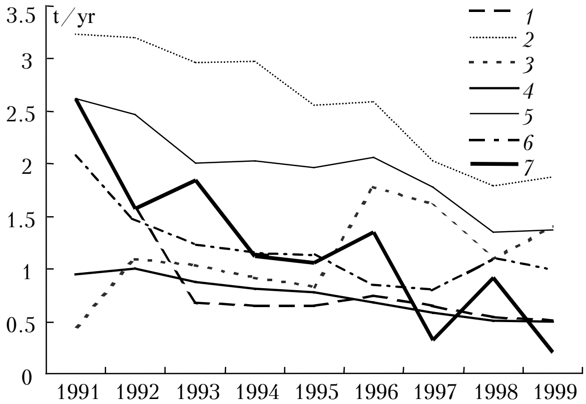

Fig. 1. Dynamics of pollutant emissions: fluorides (*1*), SO_2 (*2*), NO_x (*3*), HF (*4*), solid-state emissions $\times 10^{-1}$ (*5*), CO $\times 10^{-1}$ (*6*), inorganic dust $\times 10^{-1}$ (*7*).

The main pollutants of the urban environment are such hazardous ingredients as, for example, fluorine, beryllium, aluminum, potassium, silicon, lithium, copper, sodium, nickel, lead, vanadium pentoxide, hydrocarbons, etc.

The living matter in such environment can response not only to temporary critical increases of pollutant concentrations connected with, for example, adverse weather conditions, volley and emergency emissions, and chemical reactions. The long-term effect of some substances, even in relatively low concentrations, can also lead to their accumulation both in living organisms (provoking ultimate carcinogenic, mutagenic, and toxic effects) and on the surface (depressing the plant cover and changing the quality of surface water). Therefore, along with the absolute pollutant concentrations that are usually measured or calculated for certain hydrological and meteorological parameters, it is very important to know the dose or the period of pollutant effect on the local population and territory depending not only on the production parameters, but also on climate and orographic peculiarities of the area under study. For this purpose, we have analyzed urban climate conditions considered as the capability of the atmosphere to disperse pollutants. The most adverse months from the viewpoint of atmospheric dispersal are December and January, in which stagnant phenomena accompanied by surface and powerful elevated temperature inversions make up no less than 40%.

Using the data of many-year meteorological observations, we have calculated the functions of correlation fluctuations and the probability density of wind for the period of interest (for example, many-year month). The evolution mean concentration $\bar{s}$ of the considered ingredient was calculated by the equation

$$\frac{\partial \bar{s}}{\partial t} = -\frac{\partial \bar{u}_i \bar{s}}{\partial x_i} + \frac{\partial w_g \bar{s}}{\partial x_3} + \bar{F} + \frac{\partial}{\partial x_i}\left(N_{ji}^{(1)} \frac{\partial \bar{s}}{\partial x_j} - Q^{(1)} \right) + \frac{\partial}{\partial x_i} \bar{\nu}_{ij} \frac{\partial \bar{s}}{\partial x_j},$$

whose derivation can be found in Refs. 1–3.

The following designations are introduced here:

$$N_{ji}^{(1)} = \frac{1}{T-\tau} \int_0^{T-\tau} u'_j(t+\tau) \int_t^{t+\tau} u'_i(t_1)\, dt_1 dt\ ;$$

$$Q_{ji}^{(1)} = \frac{1}{T-\tau} \int_0^{T-\tau} u'_j(t+\tau) \int_t^{t+\tau} F'(t_1)\, dt_1 dt\ ,$$

u_i is the component of the medium velocity along the corresponding coordinate x_i ($i = \overline{1, 3}$); w_g is the rate of the gravitational sedimentation varying depending on the particle fraction; $\bar{F}$ is the mean intensity of pollution sources; t is time; ν_{ij} are the coefficients of turbulent diffusion ($i, j = \overline{1, 3}$); τ is the interval between observations; T is the considered period. Primes stand for fluctuations about the corresponding mean characteristics. Summation is conducted over the repeating indices.

The probability of hazardous pollutant concentrations for the considered period is estimated based on numerical solution of the second Kolmogorov equation written in the phase coordinate s:

$$\frac{\partial p}{\partial t} = -\frac{\partial}{\partial s}[A(t,s)\,p] + \frac{\partial^2}{\partial s^2}[B\,(t,s)\,p]$$

for the initial state $p(0, s) = p_0(s)$ and the boundary conditions $\frac{\partial (Bp)}{\partial s} - Ap = 0$ at $s \to \infty$ and $\int_0^\infty p(t,s)\mathrm{d}s = 1$.

Here $p = p(t, s)$ is the differential law of distribution of s; $A = \frac{\partial \bar{s}}{\partial t}$ and $B = \frac{1}{2}\overline{\frac{\partial s'^2}{\partial t}}$.

We have considered more than 30 hazardous pollutants emitted into the urban atmosphere by more than 160 sources of the aluminum production plant. The zones of risky pollution (from the viewpoint of violation of the accepted standards and periods of their effect on living organisms) of the environment with different substances were calculated based on mathematical models[1–3] and mapped taking into account the probability of realization of all winds occurring in the considered period.

Let us present some results calculated for one of the adverse (as to pollutant dispersal) months – January. Emissions of many substances, for example, acetone, wood dust, butyl acetate, chromium oxides, ethyl acetate, formaldehyde, aerosol oils, magnesium compounds, caustic soda, metal dust, ethyl cellosolve, lead compounds, ethyl and butyl alcohols, toluol, soot, vanadium pentoxide, do not produce concentrations hazardous for people. Pollutants, whose maximum permissible concentrations can be exceeded in one of the considered months, are tabulated below.

Pollutant	$MPC_{dayly\ mean}$	Maximum frequency of MPC excess in January, h
Benzapilene	0.000001	744
CO	3.0	85
Chrome oxide	0.002	85
Inorganic dust	0.15	576
Aluminum dust	0.001*	704
Abrasive-metal dust	0.04	576
Anhydrous hydrogen fluoride	0.005	558
NO_x	0.04	415
SO_2	0.05	28
Solid-state fluorides	0.03	246
SiO_2 dust>70%	0.05	207

* – max. volley, mg/m^3.

Figure 2 depicts the distributions of solid-state fluorides. Isoline *1* contours the zone, in which the concentration of solid-state fluorides exceeds the MPC level for no less than 48 h (a month). Isolines are drawn with the 48-h step. A special hazardous zone is the production area, in which the MPC can be exceeded as long as almost 300 h a month (see the Table and Fig. 2).

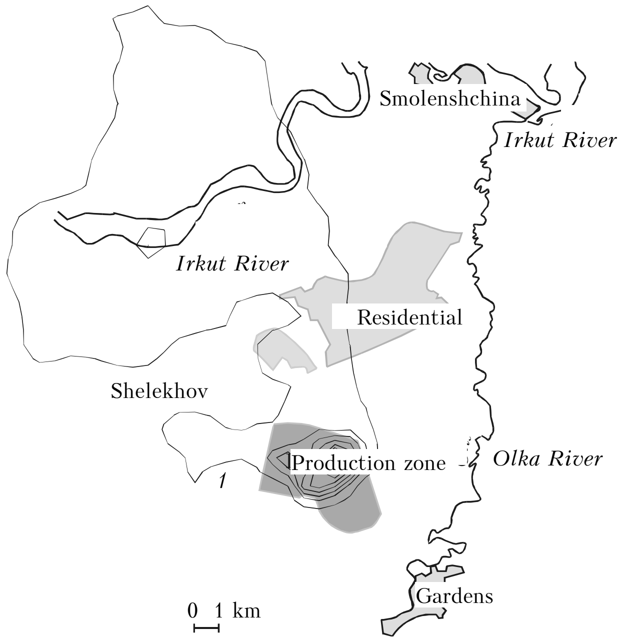

Fig. 2. Frequency of MPC excess for solid-state fluorides in January.

Particular attention was paid to polycyclic aromatic hydrocarbons, one of the widespread indicators of which is benzapilene – the substance of the first class of hazard. Benzapilene exists in the form of straw-colored water-insoluble crystals and is a rather strong and stable carcinogen. The model accounted for 29 sources of benzapilene. Figure 3 illustrates the zone of fivefold MPC excess in January. The hazardous zone has the radius of more than 6 km. Isolines are drawn with the same step as in Fig. 2.

The comparison of the results of mathematical simulation with daily observations for different pollutants (dust, carbon and nitrogen oxides, solid-state fluorides, anhydrous hydrogen fluoride, formaldehyde) at two posts of atmospheric monitoring showed close agreement. Simulation helped to reveal the contribution of the aluminum production plant to the total atmospheric pollution, as well as to give diagnostics for components that are not systematically monitored. Consideration of different prognostic models of ecological situation and selection of an optimal one can be done if data on plant reorganization are available.

It should be noted that limiting standards for some pollutants are, unfortunately, absent in Russia. The concept of the maximum permissible concentration is unclear. Criteria on pollutant effects on plants, which can be depressed at even very low pollutant concentrations, are still to be developed. Now it is necessary to consider the integral standards of media effect on living organisms with the allowance for the time of pollutant excretion and accumulation.

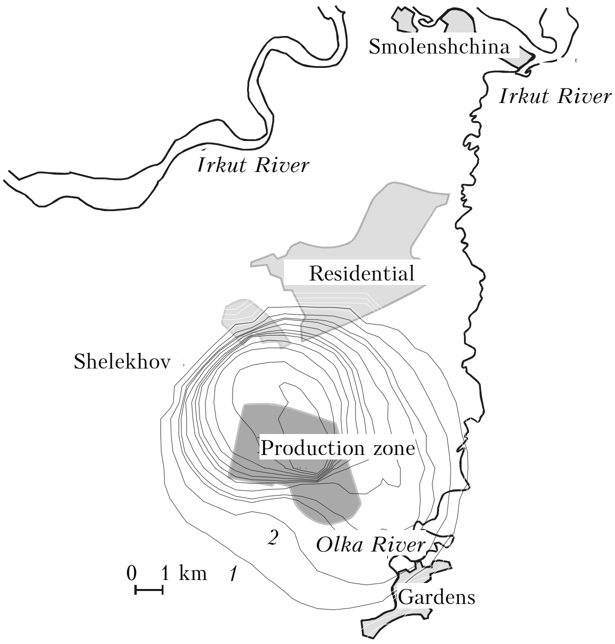

Fig. 3. Frequency of fivefold MPC excess for benzapilene in January.

The substances emitted by nonferrous metallurgy plants into the atmosphere for a long time can cause various diseases: allergy (ethyl acetate, formaldehydes), immune reactions (ecologically polluted foodstuff), cardiac abnormalities (ethyl alcohol, magnesium oxides, anhydrous hydrogen fluoride), gastroenteritis (copper, ethyl alcohol, anhydrous hydrogen fluoride, heavy metals), respiratory tract diseases (vanadium and its compounds, chrome, iron, silicon, sulfur, aluminum oxides, etc.), impairments of bearing and endocrine system (for example, salts of heavy metals), neuralgia (lead compounds, ethyl alcohol, acetone, magnesium oxides, etc.). Based on the data from Ref. 4, we have drawn the plot (Fig. 4) of the children's sickness rate (age from 2 to 17) for children of both sexes.

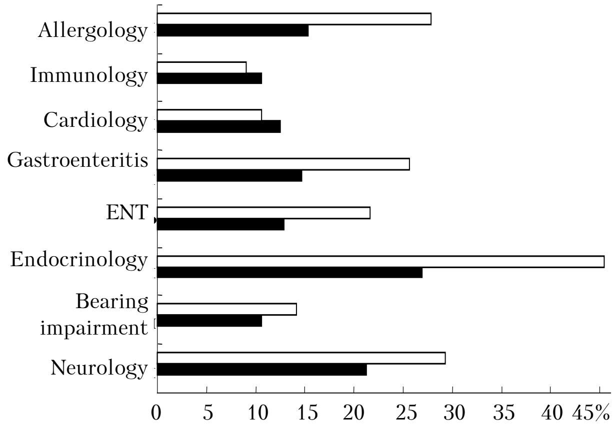

Fig. 4. Structure of children's sickness rate, in %: □ – girls, ■ – boys.

References

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