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Models of assessment of aerosol impurities in the vicinity of an oil-gas spray*

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Abstract. Based on the statement of inverse problems of pollutants transfer, the processes of formation of the long-term aerosol impurities of a certain area were theoretically studied. To this end, the properties of similarity of impurities spread processes and the statistical characteristics of wind and the turbulent conditions in the near-surface atmosphere layer were used. The quantitative models of the snow cover impurity with oil-gas sprays of the Ob deposit in the Khanty–Mansiisk Autonomy were constructed.

1. Introduction

Under conditions of ever increasing growth of the anthropogenic impact on the environment, it seems desirable to possess a comprehensive and detailed information about its true state. By the present time, theory and methods of calculation of fields of pollutants concentrations (20–30 min duration) are most well studied [1]. To define the fields of mid-seasonal, average-annual concentrations, which are based on single concentrations, a more complete information about parameters of atmospheric diffusion, meteorological conditions, the annual quantity of ejections from a source, dispersion content and impurities transformation, etc. is needed. That is the reason that many publications concerning the calculation of average-annual concentrations are restricted to an approximate assessment or an account of only separate meteorological factors, which results in the necessity of the statement of inverse problems of pollutants transfer [2, 3]. The primary sources of gas-aerosol pollutions on the Khanty–Mansiisk Territory are oil-gas enterprisers and the motor transport. The most widespread contaminating substances are the following: hydrocarbons, natural gas, oxide and dioxide of hydrocarbon, sulfur compounds, nitrogen oxides, phenols, mercaptans, etc. The advancement of oil-gas enterprisers brings about an essential anthropogenic impact on the territory of this region. Therefore, measures should be undertaken intended for increasing the ecological safety and decreasing a dangerous influence on the environment. An efficient solution to the environmental protection problem can be obtained only in the case when scientific, technical, organizational aspects are integrated into a single mechanism of control.

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2. Field exploration

The selection of snow samples in the vicinity of oil-gas sprays of the Ob oil deposit (the Khanty–Mansiisk Territory) was made on April, 21, 2004. The location of sampling points is schematically shown in Figure 1.

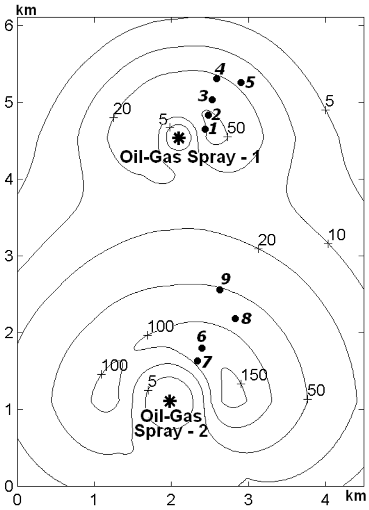

Figure 1. Scheme of selection of snow samples. The concentration fields of oil hydrocarbons (µg/l) on the territory of the Ob deposit reconstructed from the observation data

In the zone of operation of Spray 1, samples were taken at five points; in the zone of Spray 2 — at four points. A plastic tube 5 cm in diameter was used for selecting the snow samples. The state of the snow cover enabled us to employ such a sampler.

In the situation under consideration, the use of a small-diameter sampler was caused by the necessity of constraining for convenience the mass and volume of snow samples and the possibility of their consequent transportation to chemical laboratories of research institutes in Novosibirsk. Analysis of macro- and micro-component composition of snow samples was made in the Institute of Inorganic Chemistry (Siberian Branch, RAS, Novosibirsk).

3. Models of reconstructing the long-term contamination fields

The reference point for calculation of fields of the long-term contamination of a location is the following relation [5]:

$$\vec{q}_{\vec{\tau}} = \int_0^\infty q\rho_{\tau,\vec{\tau}}(q)\, dq \tag{1}$$

that expresses the connection between the average concentration $\vec{q}_{\vec{\tau}}$ for a long time period $\vec{\tau}$ and single concentrations q, referring to the time interval $\tau \ll \vec{\tau}$; $\rho_{\tau,\vec{\tau}}$ is the probability density for single concentrations. The value q is found from solution to the turbulent diffusion equation.

The meteorological conditions are especially important when calculating the mean concentration in the surface layer of the atmosphere. To them one refers the so-called normal meteorological conditions, for which one uses the power approximation of the wind speed and the vertical turbulent exchange factor [1]:

$$u(z) = u_1\Big(\frac{z}{z_1}\Big)^n, \quad K_z = k_1\frac{z}{z_1}, \tag{2}$$

where u_1 and k_1 are values of u and K_z for $z = z_1$. In this case, for a point source we obtain the following presentation for the mean surface concentration

$$\vec{q}(r,\varphi) = \iint_\Omega q(r,\varphi,k_1,u_1)p_1(k_1,u_1)\,dk_1\,du_1, \tag{3}$$

where r, φ are the polar coordinates, $p_1(k_1,u_1)$ is the joint density of probabilities u_1 and k_1 for the period of averaging, Ω is the domain of a real change of u_1 and k_1,

$$q(r,\varphi,k_1,u_1) = \frac{P(\varphi+180^\circ)q_l(r,k_1,u_1)}{r}. \tag{4}$$

Here $P(\varphi)$ is the surface wind rose, q_λ is a single concentration for a linear source.

Gas impurity. The use of power approximation (2) of the wind speed and the turbulent exchange coefficient makes it possible for a light impurity to represent $q(r,\varphi,k_1,u_1)$ in the analytical form [1,3]:

$$q_l = \frac{Q}{(1+n)k_1\varphi_0\sqrt{2\pi}r}\exp\Big(-\frac{u_1H^{1+n}}{k_1(1+n)^2r}\Big), \tag{5}$$

where Q, H are the capacity and the height of a source, φ_0 is the wind speed dispersion. For a mono-disperse impurity, the concentration is defined by the relation

$$q_\omega = q_l\chi\Big(\frac{k_1r}{u_1},\frac{w}{k_1},H\Big), \qquad \chi = \frac{[\frac{u_1}{k_1(1+n)^2}]^\omega H^{(1+n)\omega}}{\Gamma(1+\omega)r^\omega}, \tag{6}$$

where $\omega = \frac{w}{(1+n)K_1}$, $\Gamma(1+\omega)$ is a gamma-function.

The climatic analysis of the gradient observations data at the network of heat balance stations makes it possible to establish a more detailed structure and properties of the function $p_1(k_1,u_1)$. The following presentation holds [5]:

$$p_1(K_1,u_1) = p'(u_1)p''(\lambda), \tag{7}$$

where $\lambda = \frac{k_1}{u_1}$.

According to [5], we can in the first approximation assume that

$$p''(\lambda) = \delta(\lambda - \vec{\lambda}), \tag{8}$$

where $\delta(\lambda)$ is a delta-function.

For taking into account the stability parameter λ with a greater precision, the function $p''(\lambda)$ can be set as Veibull gamma-distribution

$$p''(\lambda) = \frac{\alpha^{K-1}\lambda^{-K}}{\Gamma(K-1)} e^{-\alpha/K}. \tag{9}$$

The parameters α, K of distribution (9) can be defined by the momentum method.

With the proviso that a pollution is light with allowance for (4), (5), (7), (8), from relation (3) it follows that

$$\begin{aligned}\vec{q}(r,\varphi) &= \frac{QP(\varphi+180^\circ)}{\varphi_0\sqrt{2\pi}r^2}\iint_{\Omega_1}\frac{\lambda p'(u_1)p''(\lambda)}{n+1}\exp\Big(-\frac{H^{1+n}}{\lambda(1+n)^2 r}\Big)d\lambda\, du_1 \\ &= \frac{QP(\varphi+180^\circ)\vec{\lambda}\exp\Big(-\frac{H^{1+n}}{\vec{\lambda}(1+n)^2 r}\Big)}{\varphi_0\sqrt{2\pi}(1+n)r^2}\int_0^u p'(u_1)\, du_1 \\ &= \theta_1\frac{P(\varphi+180^\circ)}{r^2}e^{-\theta_2/r},\end{aligned} \tag{10}$$

$$\theta_1 = \frac{Q\vec{\lambda}}{\varphi_0\sqrt{2\pi}(1+n)}\int_0^u p'(u_1)\, du_1, \qquad \theta_2 = \frac{H^{1+n}}{\vec{\lambda}(1+n)^2}. \tag{11}$$

Given the observations data of the impurity concentration, the parameters θ_1, θ_2 can be defined from measurements at two points by solving an appropriate system of equations. With a greater number of observation points, one should employ the least squares method.

Aerosol impurity. Consider the case of a monodisperse impurity. In the variables u_1, λ, the function χ is of the form

$$\chi = \frac{H^{(1+n)\omega_1}}{[(1+n^2)\lambda]^{\omega_1}\Gamma(1+\omega_1)r^{\omega_1}}, \tag{12}$$

where $\omega_1 = \dfrac{w}{(1+n^2)\lambda u_1}$.

From relation (3), with allowance for (4)–(8), follows

$$\vec{q}(r,\varphi) = \frac{QP(\varphi+180^\circ)\vec{\lambda}e^{-\frac{H^{1+n}}{\vec{\lambda}(1+n)^2 r}}}{\varphi_0\sqrt{2\pi}(n+1)r^2}\int_0^u \frac{p'(u_1)H^{(1+n)\vec{\omega}_1}}{r^{\vec{\omega}_1}[(1+n)^2\vec{\lambda}]^{\vec{\omega}_1}\Gamma(1+\vec{\omega}_1)}du_1, \tag{13}$$

where $\omega_1 = \dfrac{w}{(1+n^2)\lambda u_1}$.

Taking into account properties of the function $p'(u_1)$, from (13), we arrive at the following regression relation

$$q_w(r,\varphi) = \theta_{1w}P(\varphi+180^\circ)r^{\theta_{3w}}e^{\frac{-\theta_2}{r}}, \tag{14}$$

where $\omega_2 = \dfrac{w}{(1+n)\vec{\lambda}\vec{u}_1}$,

$$\theta_{1w} = \frac{QH^{(1+n)\omega_2}}{\varphi_0\sqrt{2\pi}(1+n)^{2\omega_2+1}\vec{\lambda}^{\omega_2-1}\Gamma(1+\omega_2)}, \qquad \theta_{3w} = -2-\omega_2.$$

In order that the parameters θ_{1w}, θ_2, θ_{3w} be assessed, it is necessary in regression (14) to carry out observations no less than at three points of a location. The number of points can be decreased if θ_2 were preliminarily estimated for the source in question provided a pollution is slowly precipitating. The parameter θ_2 is, in a sense, external and can be preliminarily assessed on the basis of the geometric height of a source and the dynamic and the thermal characteristics of a rejected gas-air compound.

4. Reconstruction of concentration fields and evaluation of model parameters

The sprays under study refer to the most powerful and steadily operating sprays on the Khanty–Mansiisk territory. They are in agreement with requirements of model (14). Figures 2, 3 present the results of recovery of a continuous picture of contamination of the neighborhood of sprays 1 and 2—by oil and polyaromatic hydrocarbons (OH, PAH), aluminum, manganese.

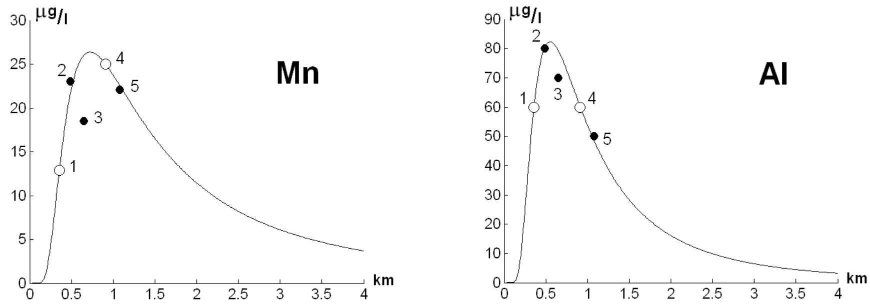

Figure 2. Recovery in the snow of the concentration sum value of Mn, Al along the sampler route

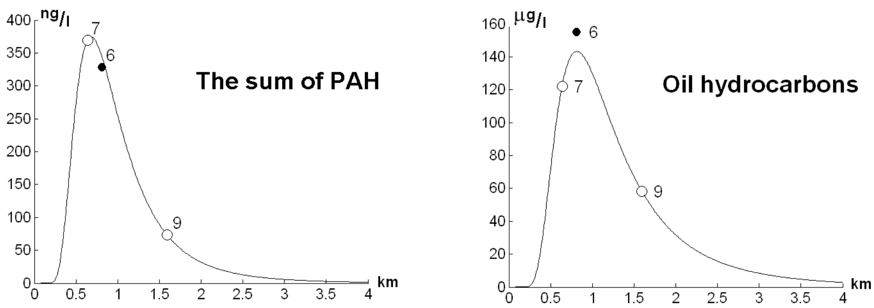

Figure 3. Recovery in the snow of the sum concentrations value of polyaromatic hydrocarbons, oil hydrocarbons

The observations data marked with dark circles were used for assessing regression parameters (14). The light circles indicate to the level of correspondence of control observations to the calculation (a continuous curve). For the first spray, the assessment of 0.8 km was taken for $r_{\max}$, for the second spray — about 2 km.

Analysis of Figures 2, 3 show that an agreement between the calculations and observations is, on the whole, quite satisfactory. A considerable discrepancy in the results of modeling of polyaromatic hydrocarbons and hydrocarbons at certain points (points 5, 8) can be associated with the proximity of the motor track.

The calculations conducted indicate to the fact that in order that a continuous picture of contamination of a location be recovered, only two points of the route of a sampler are needed. The rest points of a sampler can be used to control the accuracy of recovery of fields of aerosol contamination.

5. Assessment of the summary precipitation

According to the snow sampling data, the average moisture supply in the vicinity of the sprays in question is about 82 l/m^2. With allowance for this value and the rose of winds in the winter season, integration (14) over a sufficiently large area makes it possible to obtain an assessment of the summarized content in the snow of polyaromatic hydrocarbons, oil hydrocarbons, macro-components and base metals in question. The table presents assessments of their summarized content in 4×4 km squares. The sprays located in the centers of these squares. It should be noted that the obtained assessments of the emission intensity of dangerous pollutions are estimations from below because the polydispersion effects both in the vicinity of a spray and at remote distances from it are not completely taken into account.

Assessment of parameters of aerosol ejections

Component	Assessment of parameters		Summarized ejection, kg
	θ_1	θ_2	
Spray 1			
The sum of	0.237	4.46	0.017
Hydrocarbons	133.0	4.29	9.1
Zink	264.8	3.32	9.1
Chloride	4.6	3.32	0.48
Aluminum	266.5	2.90	28.1
Manganese	117.7	2.21	13.9
Spray 2 (OH, PAH)			
The sum of	13.9	5.88	0.1
Hydrocarbons	7089	4.92	56.2

Analysis of tables show that the values θ_2 undergo a distinct change. This means that the sediment rate and, respectively, the mean size of particles, containing the components in question, will be different. Hence, zones of influence and maximal sedimentation will be different as well. The parameters θ_1 are proportional to the capacity of impurity ejection components and depend on the sediment rate of appropriate aerosol fractions. The summarized sedimentation is found from a combination of these values.

6. Conclusion

The carried out theoretical and experimental studies as well as the numerical analysis of the observational data in the vicinity of oil-gas sprays with intensive burning modes allow the following conclusions:

1. The numerical models proposed fairly adequately describe the processes of the long-term aerosol contamination of a location with burning products of an accompanying oil gas. The reliability of a multi-component recovery of pollutants fields by the observation data is to a large extent due to the presence in their measurements content of tracer elements and substances. The numerical analysis of the data of monitoring the snow cover in the vicinity of sprays indicate to the existence of sufficiently simple regularities of forming the fields of the long-term contamination of a location.

2. The developed reconstruction models make possible to perform an indirect control of spray ejections using a limited number of sampler points. The carried out experiments and verification of the models proposed have shown their efficiency and satisfactory accuracy of the recovery of fields of the long-term multi-component contamination of a location.

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