Model of control over polluting emissions into the urban atmosphere

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A model is proposed for optimal control over emissions of harmful pollutants into the urban atmosphere based on the annually mean pollution indices. As a goal function, it uses the total damage to human health caused by the atmospheric pollution. The main additional condition in the optimization model is a restriction imposed on the resources of controlling the productivity of pollution sources. An optimal reduction of ash dust emissions from 67 coal boiler houses in Belovo town, Kemerovo Region, was numerically simulated.

Introduction

Significant potential for protection of the urban atmosphere lies in optimization of the control over polluting emissions. Such a control must take into account the technological features of sources, arrangement of buildings, and local atmospheric circulations. To find optimal solution of the problem, one should have information on the fields of pollutants concentration, cost of decreasing the emission intensity from every source, and the damage inflicted by atmospheric pollution to the environment. The efficiency of the control should be determined from the cost of the decrease of polluting emissions keeping in mind the sanitary, hygienic, and social requirements on quality of the atmosphere.

Statement of the problem

Let there be N sources with the strengths Q_n, $n = \overline{1, N}$, in the area Ω. In view of the principle of superposition, the field of the near-surface concentration from the set of sources is determined by the following equation:

$$q(x, y, Q) = \sum_{n=1}^{N} Q_n \Psi_n(x, y), \qquad (1)$$

where $\Psi_n(x, y)$ is the concentration produced by the nth source of unit power (1 g/s).

Denote the decrease in the strength of the nth source as e_n; $0 \le e_n \le Q_n$. Then the concentration for the changed strengths takes the form[1,2]:

$$q(x, y, \mathbf{Q}, \mathbf{e}) = \sum_{n=1}^{N} (Q_n - e_n)\Psi_n(x, y). \qquad (2)$$

Let the damage due to atmospheric pollution at the point $(x, y) \in \Omega$ be proportional to the annually mean concentration

$$f(x, y) = A(x, y)q(x, y), \qquad (3)$$

where A is the specific damage to human health at the considered point.

Assume that

$$A(x, y) = C p(x, y), \qquad (4)$$

where $p(x, y)$ is the population density; C is the specific damage to the human health due to pollution of a unit area with a given population density. Then the total damage to the human health in the area σ is

$$F(\mathbf{e}) = \int_{\sigma} C p(x, y) q(x, y, \mathbf{e}) \mathrm{d}x\mathrm{d}y. \qquad (5)$$

Taking Eq. (5) as a goal function, we come, as a result, to the problem of minimizing the damage to human health due to atmospheric pollution

$$F(\mathbf{e}) \to \min_{\mathbf{e} \in E} \qquad (6)$$

at the following restriction imposed on controlling resources:

$$G(\mathbf{e}) \le G_0, \qquad (7)$$

where

$$G(\mathbf{e}) = \sum_{n=1}^{N} G_n(e_n); \qquad (8)$$

$G_n(e_n)$ is the cost of decreasing the emission of the nth source; G_0 is the total funds for decreasing the emissions; $E = \{\mathbf{e}\colon\ 0 \le a_n \le e_n \le Q_n,\ n = \overline{1, N}\}$ is the domain of the simplest restrictions, a_n is the permissible decrease of emission for the nth source.

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Note 1. Let the cost function have the form

$$G_n(e_n) = ke_n.$$

In this case, the problem (6)–(8) with allowance for Eq. (2) is a linear-programming problem, and it can be solved by standard methods.

Note 2. If positions of the sources are included into the consideration as sought parameters, then the problem (6)–(8) can be reduced to solution of a nonlinear-programming problem. Such a problem is examined in Ref. 3.

Note 3. Restrictions on the maximum permissible concentration (MPC) can be included into the problem (6)–(8) as additional conditions. In this case, the problem of control over emissions may be unsolvable.

Models for calculation of the annually mean pollutant concentration

One of the principal points in development of models for optimization of control over emissions is a selection of the model for calculation of annually mean pollutant concentrations. For calculation of the annually mean concentrations, the corresponding distributions of the wind speed and direction and the character of stability of the atmospheric boundary layer are used; then all results are summed up with allowance for repetition of hydrometeorological situations.

The equation for the near-surface annually mean concentration based on the International Atomic Energy Agency technique[4,5] for a single source has the form

$$q(x, y) = \frac{Q}{2\pi} \sum_i R_i \exp\left[-\frac{y^2}{2\sigma_{yi}^2}\right] \times$$

$$\times \left[\exp\left[-\frac{(z-h)^2}{2\sigma_{zi}^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_{zi}^2}\right]\right] / (U_i \sigma_{yi} \sigma_{zi}), \quad (9)$$

where Q is the intensity of the source; h is its height; σ_{yi} and σ_{zi} are plume dispersions in the horizontal and vertical directions; U_i is the wind speed at the height of the source; R_i is the distribution function of repetition of a hydrometeorological situation for the ith plume (this function is determined from climatic data).

Calculations by model (9) for Kemerovo are given in Ref. 6. A good agreement between the calculated concentrations and those measured at stationary posts is demonstrated.

If the hydrometeorological information is insufficiently complete, the wind rose should be taken into account in the first turn.[7] The MGO (Main Geophysical Observatory) technique is useful in this case.[8,9] It allows one-time concentrations to be calculated at limited requirements on the input information.

The input meteorological parameters of the MGO model are the wind speed and direction at the wind vane level and the temperature of air.

The repetition of the hydrometeorological situation in this case is determined by the annually mean wind rose and the annually mean air temperature.

Numerical simulation of optimal emission conditions

Let us consider some examples of numerical solution of optimization problems as applied to distribution of resources in order to reduce emissions of ash dust from boiler houses in the central part of Belovo. The aim of calculations is to demonstrate the possibility of applying the proposed controlling models to specific sources of pollution of the urban atmosphere and to provide them with the available input information. The preliminary to solution of the optimization problems is calculation of annually mean concentrations of ash dust. Based on the input data, we selected the MGO model. The list of sources to be regulated included 67 boiler houses situated in the central part of Belovo, Kemerovo Region. The data on the parameters of the sources: their height, stack diameters, strength, temperature and amount of emitted gas-air mixture, and the degree of cleansing, were borrowed from Ref. 10.

The cost of reduction of emissions of the nth source was assumed proportional to the value of emission reduction e_n with a constant coefficient k for all the sources. In this case, the total cost function of damage regulation takes the following form:

$$G(\mathbf{e}) = k \sum_{n=1}^{67} e_n. \quad (10)$$

In numerical experiments, the total reduction of ash dust emission was assumed equal to 300 g/s, i.e., the controlling resource in this case is

$$G_0 = 300k. \quad (11)$$

The coefficient k should not necessarily be set in such a formulation of the problem, because Eqs. (10) and (11) allow it to be excluded from the restriction (7).

The relative decrease of the source strength was varied from 0 to 50%. The population density in the suburban and urban parts was assumed 1:10.

Figure 1 shows the initial annually mean concentrations created by the boiler houses. Figure 2 shows the results of simulation of the near-surface concentration field after optimal reduction of emissions. For the linear cost function (10), the value of specific damage due to emission (1 g/s) of a single boiler house is a representative characteristic. It is determined by the source height to a great degree. The Table gives the dependence of the specific damage on the height of stacks of the boiler houses situated in the central part of Belovo. These data demonstrate that the damage significantly depends on the stack height.

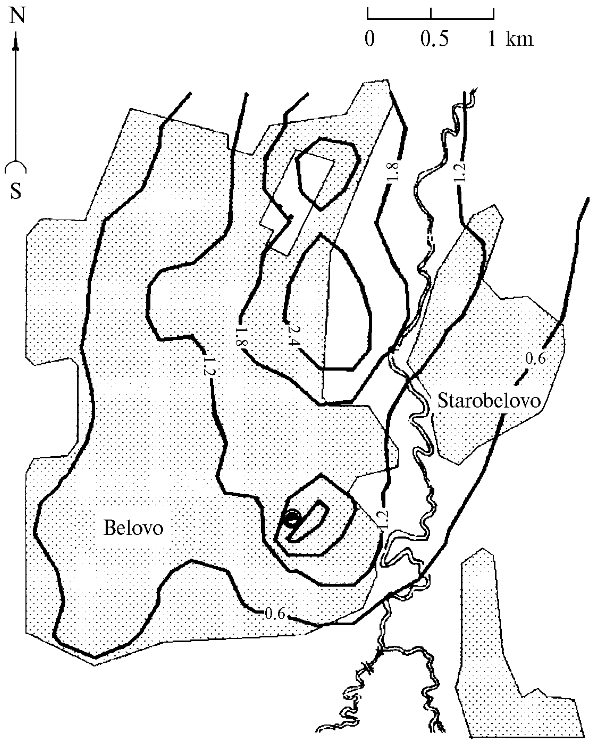

Fig. 1. Initial field of annually mean concentration (mg/m^3) of ash dust produced by boiler houses in Belovo.

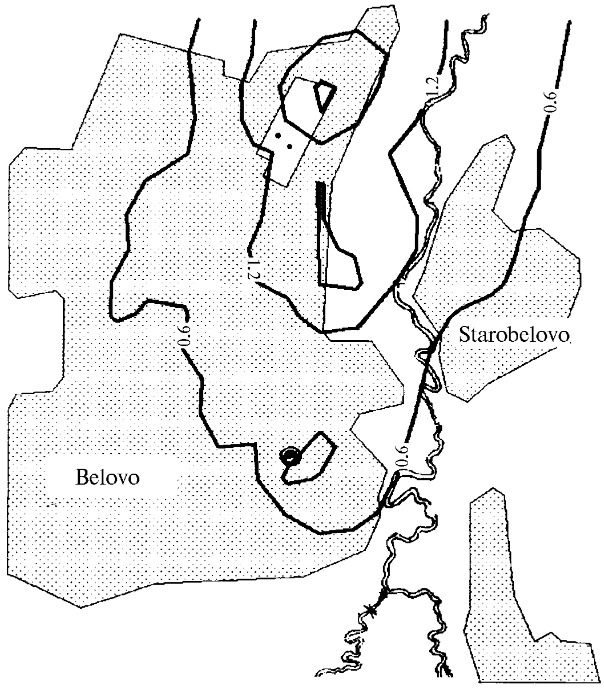

Fig. 2. Field of the annually mean concentration (mg/m^3) after optimal total reduction of ash dust emissions by 300 g/s.

Analysis of results of numerical simulation shows that the list of the sources to be regulated includes mostly low stacks. This circumstance is explained by different dispersion capability of plumes from low and relatively high stacks within the urban territory. As follows from the figure, after reduction of emissions the distribution of isolines of the concentration field becomes lower-contrast.

Table. Specific damages due to ash dust emissions of boiler houses situated in the central part of Belovo

Stack height, m	5	10	15	30	45
Specific damage	14.5	9.9	7.7	3.6	1.9

Conclusion

The conducted numerical experiments demonstrate the applicability of the proposed optimization models to reducing emissions within the framework of the available input information on the sources of pollution of the urban atmosphere, population density distribution, and meteorological conditions. The optimization models are constructed for a single-component pollution. In the case of multicomponent pollution, they should be somehow modified because of appearance of additional conditions.

The cost of the emission reduction may significantly differ for different pollutants. It should be noted that determination of the cost function is a complicated problem, which requires an information on specific character of a source and the manufacturings, technologically and economically connected with them.

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