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The use of satellite information to estimate smoke emissions parameters of power stations*

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Abstract. The satellite observations of smoke plumes from the pipes of power stations make possible to obtain prompt information about the processes of impurities distribution in the atmosphere and about the source parameters. This paper proposes a method of numerical reconstruction of characteristics of the active stage of the smoke stream elevation. The models for evaluating the processes of the gas-air mixture rising from a source under the influence of dynamic and thermal factors are discussed. As the basic relations, analytical solutions to the equations of hydrothermodynamics in the axially symmetric approximation are used. Using the winter satellite images, the numerical analysis of the active phase of smoke plumes elevation from the pipes of the Novosibirsk power stations has been carried out.

Keywords: satellite images, plume, buoyancy flow, atmosphere, hydrodynamics equations, impurities elevation height.

Introduction

The research into atmospheric pollutions from anthropogenic and natural sources is a matter of current interest. Such a study makes possible to determine the degree of impact of harmful impurities on ecosystems and to assess the risks to the health of population [1–3].

Ground-based observations of the smoke pollution propagation are fairly limited. The smoke plumes from industrial plants, large power plants, and natural fires are well visualized in satellite images [4–6]. The use of satellite images allows a detailed track of active and passive phases of the smoke torches propagation. Trajectories of plumes indicate to the speed and direction of the wind at emission heights. These trajectories can be traced at remote distances [5, 7, 8]. This picture is typical in the winter period.

The models based on the numerical solution to the equations of hydrothermodynamics of the atmosphere make possible to obtain a detailed picture of the impurity propagation at local and regional scales [9–14]. To carry out the calculations, a large amount of information is required, including that on the meteorological conditions and characteristics of impurity

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emission sources [1, 7, 15]. Thus the basic parameters of sources such as effective height of elevation of a smoke plume and emission intensity require a greater accuracy of detection. Information about the vertical wind profile is also important.

To solve the problems of estimating the emission parameters, the information from aerological and meteorological stations and satellite images is required [4, 8, 16]. As the basic relations, the equations of hydrothermodynamics of the atmosphere, transport and the impurity diffusion must be used [12, 17]. As a result, this will make possible to increase the accuracy of calculation of the pollution fields.

1. Objects and materials of research

The research materials were winter satellite images of the territory of the city of Novosibirsk. In these images, the trajectories of smoke emissions from the pipes of Power Station 2 (PS-2) and Power Station 3 (PS-3) are clearly seen. The height of the main pipes of PS-2 and PS-3 is 120 m, their diameter is 8.2 m. Figure 1 shows a snapshot of the city of Novosibirsk taken at the

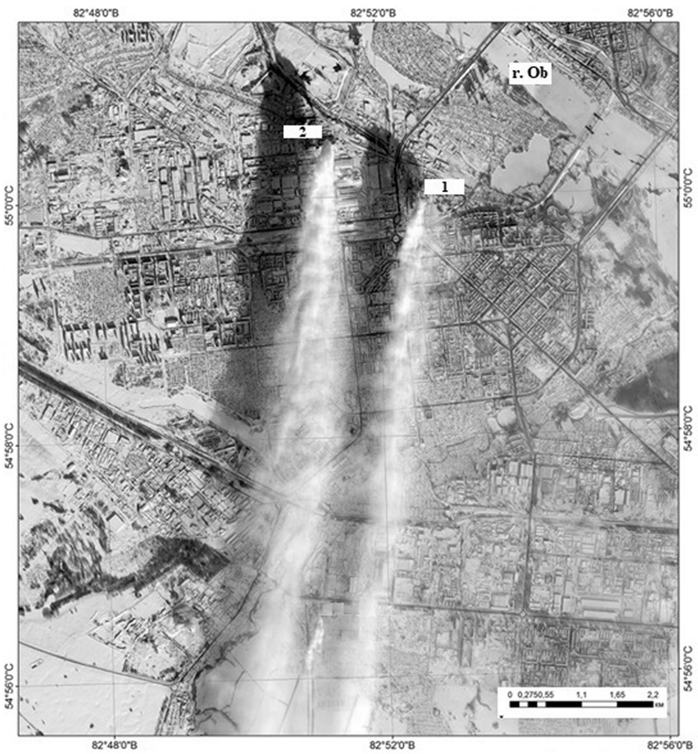

Figure 1. A satellite image of the city of Novosibirsk for February 1, 2019 at 12:10 of local time from the Canopus-B satellite No. 4: 1 — PS-2, 2 — PS-3

Siberian Division of "Scientific Research Center of Space Hydrometeorology PLANETA" (http://www.rcpod.ru).

A preliminary analysis of this image shows the uniform nature of the direction of impurity emission from the pipes of PS-2 and PS-3. The smoke plumes from the pipes of PS-2 and PS-3 are brought to the south direction. The elevation height of gas-air mixture coming from the pipes stations attains a few hundred meters. Smoke jets are located within the winter atmospheric boundary layer. Such a situation, as a rule, takes place with light winds in the lower atmosphere.

Table 1 provides the information on meteorological conditions for February 1, 2019 according to the Novosibirsk aerological station. The aerological station is located at a hight of 143 meters above the sea level. The table shows the height distributions of the main meteorological values for the day in question: atmospheric pressure, temperature, direction and speed of the wind at 7:00 and 19:00 of local time.

From Table 1 it follows that at 00 UTC, the temperature stratification was close to the neutral one in the layer above the pipes of PS-2 and PS-3 and at the surface, the inversion temperature distribution was observed. At 12 UTC, up to a height of about 300–500 meters from the ground the neutral stratification of the atmosphere was preserved, and higher the temperature inversion was observed. At the heights of the atmospheric boundary layer, weak north-north-west winds were observed. Table 2 represents the data of the weather station "Ogurtsovo" located near to the city of Novosibirsk.

Table 1. Meteorological parameters in the lower atmosphere according to the aerological station in Novosibirsk (index 29634) on February 1, 2019

Time, UTC	Height, m	Pressure, hPa	Temperature, °C	Wind direction, degree	Wind speed, m/s
00	143	1015	−32.9	20	4
	248	1000	−31.9	20	5
	787	927	−27.1	5	8
	803	925	−27.1	5	08
	1080	890	−27.5	1	10
	1154	881	−27.1	0	10
	1412	850	−25.9	355	10
12	143	1024	−31.7	280	2
	310	1000	−32.9	285	3
	338	996	−33.1	295	3
	476	977	−31.8	345	4
	867	925	−27.9	340	4
	1308	870	−26.1	340	6
	1476	850	−26.3	340	7

Table 2. The data from the meteorological station "Ogurtsovo" (index 29638) on February 1, 2019

Time, UTC	Wind direction	Wind speed, m/s	Temperature, °C
00	North	2	−33.3
03	North	2	−34.3
06	South	1	−32.5
09	West	3	−31.9
12	West	1	−34.3
15	South	2	−36.8
18	South	1	−39.2
21	South	1	−38.5

From Table 2 it is evident that during the day, weak winds of unstable directions were observed. February 1 is characterized by very low air temperatures with a weak daily variation.

2. Estimation of the characteristics of the smoke mixture elevation

For the simulation of the processes impurities propagation in the atmosphere, one needs the information on the current parameters of emission sources, including an additional elevation of a smoke plume [1, 3, 18, 19]. It is due to the characteristics of the gas-air mixture: temperature and velocity of gases outgoing from the pipe. The stratification of temperature, air humidity and the wind speed distribution strongly affect the processes of impurity propagation [1, 17, 20].

There are different approaches to describing the characteristics of the active phase of the smoke plume elevation [3, 18, 21]. One of them is in determining the effective height of the outgoing gases. A more universal approach is based on solutions of the equations of hydrothermodynamics of the atmosphere combined with the equation of transport and diffusion of impurities [3].

2.1. Determining the effective height of a source. After outgoing from the source, the overheated impurity gradually rises to a certain height, which is considered to be effective. In this case, the actual height the emission source is determined by the expression [1, 22]:

$$h_{\text{eff}} = h_{\text{st}} + \Delta h, \tag{1}$$

where h_{st} is the geometric height of the pipe, Δh is an addition to the height due to the dynamic and thermal factors.

When the stratification is close to neutral, the calculation of Δh is performed according to the formula [1]:

$$\Delta h = a\frac{w_0}{U}D_0 + b\frac{\Phi}{U^3}, \quad \Phi = gw_0\frac{D_0^2\Delta T}{4T_a}, \tag{2}$$

where w_0 is the rate of the impurity emission into the atmosphere, U is the wind speed, D_0 is the inner diameter of the pipe, Φ is the buoyancy flow, g is the acceleration of gravity, ΔT is an increase in the temperature of outgoing gases as compared to the temperature of the atmosphere T_α. When measuring the wind speed at the level of a wind vane: $a = 1.9$, $b = 4.95$ [1, 3].

2.2. Estimation of the elevation velocity and temperature of a smoke mixture. The concept of the effective source height is not well defined. As a result, this can lead to significant errors in the simulation of the concentration field. More reliable are the methods for estimating the smoke jet propagation, based on the integration of the equations of motion and heat influx [3, 21]. For the case of the neutral atmospheric stratification in the axially symmetric approximation, the vertical elevation rate w and the overheat temperature ϑ can be explicitly described [21]:

$$w(z,r) = w_m(z)f(\alpha), \quad \vartheta(z,r) = \vartheta_m(z)f(\alpha), \tag{3}$$

where z is the distance from the source in the vertical direction, r is the distance from the axis of the smoke stream,

$$w_m(z) = \Big(\frac{A}{z} + \frac{B}{z^3}\Big)^{1/3}, \tag{4}$$

$$\vartheta_m(z) = \frac{G}{z^2}\Big(\frac{A}{z} + \frac{B}{z^3}\Big)^{-1/3}, \tag{5}$$

$$f(\alpha) = e^{-\alpha^2/2}, \quad \alpha = \frac{r}{R},$$

A, B, G are some constants, R is the effective radius of the jet. According to [21], the expansion of the smoke stream in the active elevation phase is described by the relation

$$r = cz, \tag{6}$$

where the parameter c is determined from observational data.

3. Results and discussion

The satellite image shown in Figure 1 allows the study of the active phase of the elevation of smoke plumes from the pipes of PS-2 and PS-3 of Novosibirsk. An important information was obtained based on the analysis of the shadows of plumes on the earth's surface. The angle of the height of the sun and the measured projections of smoke plumes from the PS- pipes the height impurities elevation was determined. In this case the height of the sun above the horizon attains 17°, the distance between the upper edge of the shade of the plume and the PS-3 was 1050 m. It follows that the additional height of the smoke jet elevation reached 307 m.

According to Tables 1, 2, during a day a weak wind was observed. In such circumstances, the calculation of additional elevation heights of smoke plumes from the pipes of PS-2 and PS-3 for formulas (1), (2) brings about large errors in their determination and the result of calculation is of minor importance. The application of relations (3)–(5) may be more effective. To this end, it is necessary to determine the values A, B, G from the observations of smoke plumes. Using (4), we obtain the following system of equations for finding A, B:

$$\frac{A}{z_0} + \frac{B}{z_0^3} = w_0^3, \quad \frac{A}{h + z_0} + \frac{B}{(h + z_0)^3} = m^3 w_0^3. \tag{7}$$

Here w_0 is the rate of the gas-air mixture emission from the pipe, z_0 is determined using relation (6) according to the inner radius of the pipe orifice r_0, h is equal to the height of the plume elevation to a level close to a maximum, m is the extent of decreasing w_0 in the upper section of the smoke stream elevation. In general, the solution to the system of equations (7) has the form

$$A = w_0^3 \frac{m^3(h + z_0)^3 - z_0^3}{(h + z_0)^2 - z_0^2}, \quad B = w_0^3 z_0^2 (h + z_0)^2 \frac{z_0 - m^3(h + z_0)}{(h + z_0)^2 - z_0^2}. \tag{8}$$

Using the satellite image (see Figure 1), the parameter c is calculated by the formula $c = \frac{r_1}{h_1}$, where h_1 is the distance along the axis on the projection of the active phase of the smoke stream elevation ($z_0 < h_1 \leq h$), r_1 is the radius of the projection of the ejection cone at a distance h_1. The parameter G is found from relation (5):

$$G = \Delta T z_0^2 \Big(\frac{A}{z_0} + \frac{B}{z_0^3}\Big)^{1/3}. \tag{9}$$

Figure 2 presents the calculations of the rate of the gas-air mixture elevation along the axis of the plume from the pipe of the PS-3 for various rates w_0.

Using a satellite image (see Figure 1) and relation (6), an estimate of the height z_0 was carried out. It was 74.5 m. For the calculation of h, the projection length of the active phase of the plume and the angular height of the sun, measured in the snapshot, were used. Given the obtained values z_0,

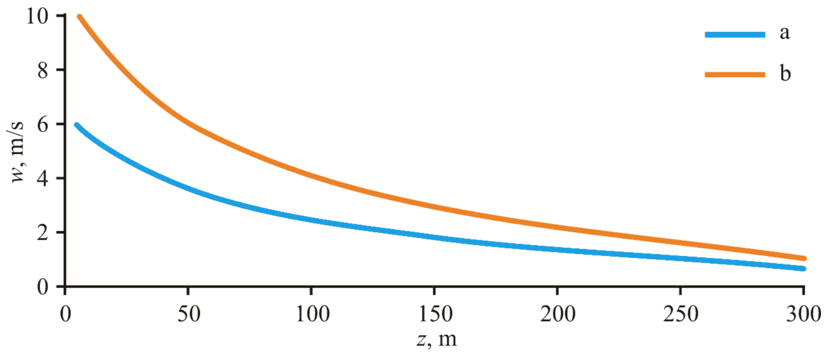

Figure 2. The estimation of the rate of the smoke plume elevation of PS-3 for $w_0 = 6$ m/s (a) and 10 m/s (b)

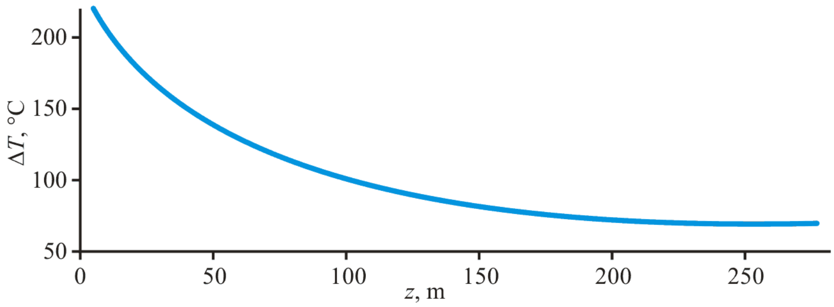

Figure 3. The temperature change along the plume axis

h, the parameters A, B were calculated by formula (8). In the calculations, the parameter value m was assumed to be 0.1. The analysis of Figure 2 shows that at the initial stage of the active phase of the elevation (80–100 m from the orifice of the pipe), the rate of elevation of the plume sharply falls, then rather a smooth decrease occurs.

Figure 3 shows the temperature change with height along the plume axis calculated by formula (9). The difference between the temperatures of the gas-air mixture and emission outgoing from the pipe and the surrounding air was assumed to be 220°C.

In Figure 3, the course of a change with the height of the plume temperature is similar to a change in the rate of its elevation (see Figure 2). Nevertheless, the rate of the temperature drop in the area above 100 meters is lower, and its value in the upper part of the plume is significantly higher than the temperature of the surrounding air. Whereas according to observations (see Figure 1), the plume temperature in the upper phase of the elevation must approach the temperature of the air in the atmosphere. This discrepancy is a consequence of the assumption that the amount of heat in the plume is constant in the process of the derivation of formulas

(4), (5) [3, 21]. For the construction of adequate models of evaluation parameters of smoke plumes with different types of temperature stratification in the atmosphere requires the use of a more detailed description of hydrodynamic processes. In this case, it is necessary to bring the system of equations to a dimensionless form.

4. Conclusion

Using the solutions to the equations of hydrothermodynamics of the atmosphere, a model for estimating the elevation of the gas-air mixture from a source under the influence of dynamic and thermal factors is proposed. The application of the analytical representation of the solutions of the system of equations of motion and heat influx for a neutrally stratified atmosphere made it possible to obtain estimates of the model parameters in the explicit form. Based on the winter satellite image, the numerical analysis of the active phase of the smoke plume elevation of the power stations of Novosibirsk was carried out. The relations for calculating the vertical rate of elevation and temperature changes in the smoke stream in the lower atmosphere have been obtained.

The application of the approach proposed is most effective in the winter period. The satellite images, due to the snow surface, are provided with color homogeneity of the earth's surface. Under such conditions, the highest contrast of the shadow of the plumes to the surface is observed. Using the satellite observations allows one to obtain an objective estimate of the height of the smoke plume. To develop the methods for assessing the characteristics of the smoke plumes elevation with stable and unstable stratification of the atmosphere, a numerical solution to the equations of hydrothermodynamics of the atmosphere is required.

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