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EMISSIONS OF POLLUTANTS INTO THE ATMOSPHERIC AIR BY STATIONARY SOURCES*

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Abstract

Oil and gas companies are one of the main sources of man-made hazards associated with the emission of extremely harmful substances and extreme situations. Emissions of harmful substances during the operation of oil and gas facilities complicate the environmental situation. Environmental issues are always actual. The purpose of this work is to analyze the dispersion of pollutant emissions into the atmosphere by stationary sources. The research was addressing the issues of analysis of ground-level concentrations of pollutants within a sanitary protection zone. The object of the study is the enterprises of the oil and gas complex, the subject of the study is the estimation of emissions of harmful substances into the atmosphere by stationary sources. Emissions of pollutants were calculated using a Gaussian statistical model. Mathematical models for the determination of lateral and vertical diffusion coefficients were constructed. The analysis of pollutant emissions into the atmospheric air by stationary sources of different altitudes was performed. It is established that the concentration of the pollutant from the source decreases monotonically. The bulk of impurities is concentrated in a relatively narrow jet. The lower the source, the closer to it the maximum concentration of air pollutants is, resulting in a negative impact on the health of service personnel.

Keywords: concentration, oil and gas complex, pollutant emissions, statistical model

1. Introduction

Hazardous emissions of substances and extreme situations at oil and gas enterprises may be accompanied by accidents, explosions, fires and environmental pollution. The risks of the environmental impact of these enterprises are related to the following activities:

- geological research and prospecting;
- development of oil and gas fields;

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- transportation of hydrocarbon energy via main and industrial pipelines;
- storage of oil and gas;
- supply of natural and liquefied petroleum gas to industrial consumers and to the population of cities and villages, etc.

It should be noted that the main task of the environmental policy of oil and gas enterprises is to ensure efficient operation, reduce environmental risks in the production process and implement international environmental standards. In order to achieve this goal, the company management has made the following commitments:

- protection the environment and minimizing of negative impact on it;
- compliance with the mandatory requirements of the legislation and other requirements that the company is obliged to fulfill in the field of environment;
- implementation and improvement of the environmental management system in accordance with the requirements of the international standard ISO 14001: 2015;
- adherence to the principle of dynamic economic development with the most rational use of natural resources and preservation of a favorable environment;
- consideration of environmental factors when planning activities and procurement of technology, materials, equipment, works and services;
- improving the efficiency of production processes by applying the best available technologies;
- ensuring targeted planning of actions aimed at preventing and reducing the negative impact on the environment, using a risk-oriented approach;
- raising the environmental culture and employee awareness of their role in addressing environmental issues;
- ensuring accessibility of information on activities related to environmental impact (Naftogaz, 2017, 2018).

Despite the extensive work on environmental protection, oil and gas companies are at increased risk of danger.

The environmental impact of oil and gas companies is the emissions of pollutants and greenhouse gases into the air, water consumption; waste generation; accidental emissions or spills of pollutants.

Emissions of harmful substances during the operation of oil and gas facilities complicate the environmental situation. Therefore, solving environmental problems is always actual. The urgency is to reduce the technogenic impact.

Many scientific papers have been devoted to the problem of pollutant emissions into the atmosphere, namely: (Adamenko, 2017; Hinds, 1999; Jørgensen, 1997; Sharan et al., 2006; Stockie, 2011; Turner, 1994).

From the analysis of the literature on the issue of pollutant emissions, it follows that there is a need for a comprehensive analysis of emissions that will allow effective measures to be taken to minimize environmental pollution. To conduct a comprehensive analysis, it is necessary to select a model to describe the dispersion of pollutants in the air. The model should take into account the conditions of the task and the amount of input data available to solve it.

The most common classes of pollutant dispersion models in the air are the empirical-statistical classes (Berlyand, 1991; Mokin et al., 2016).

The empirical-statistical models are as simple as possible and cannot provide the necessary accuracy for estimating atmospheric air quality. However, they may be used to analyze average annual air pollution and may indicate the need or feasibility of a more accurate assessment of the environmental risk of atmospheric pollution in a given area. One of the most common in the world among these models is the Gaussian pollutant dispersion model, which is used to analyze pollutant emissions by stationary sources.

The purpose of this work is to analyze the dispersion of pollutant emissions into the atmosphere by stationary sources. The research was addressed the analysis of surface concentrations of pollutants within the sanitary protection zone, which will allow in the future during the design of similar facilities to determine the optimal height of the source of pollution to minimize the impact of emissions on the health of staff. The object of the study is the enterprises of the oil and gas complex, the subject of the study is the estimation of emissions of harmful substances into the atmosphere by stationary sources.

2. Material and Methods

The oil and gas enterprises were taken to estimate the emissions of harmful substances into the atmosphere. Atmospheric pollutants were 45.1 thousand tons in 2017 and 67.0 thousand tons in 2018. That is, they were increased by 48.5 %. For the analysis of pollutant emissions at the oil and gas enterprises the materials from the annual reports for 2014-2018 were used.

According to the statistics (Naftogaz, 2017, 2018), a chart of emissions of pollutants into the air by the enterprises for 2018 was drawn (Fig. 1). As the major part of the emissions are carbon monoxide impurities, nitrogen compounds and non-metallic volatile organic compounds, their environmental impact should be analyzed.

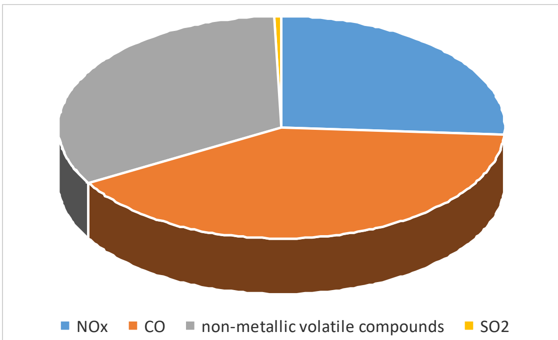


Fig. 1. Emissions of pollutants into the atmosphere

An analysis of statistics by oil and gas companies for 2018 on the amount of pollutants released into the atmosphere indicated a significant increase in carbon monoxide emissions in 2018. In 2017 the total amount of carbon monoxide emissions was 19.7 thousand tons, while in 2018 – 27.2 thousand tons. Fig. 2 shows the nature of changes in carbon monoxide emissions at oil and gas companies during 2014-2018. To describe the nature of the change in carbon monoxide emissions over the study period, a trend line was constructed based on a scatter plot based on actual data. From Fig. 2 it follows that measures should be taken to reduce further air pollution. To estimate air pollution by carbon monoxide, we will calculate the maximum annual emissions at one of the plants, namely: 14.6 thousand tons/year. This will allow the estimation of the nature of the emissions into the atmosphere with the maximum pollutant emission rate and the timely application of measures to reduce their environmental impact. Consider the dispersion of pollutant emissions into the atmosphere by stationary sources during the operation of oil and gas facilities. A stationary emission source is a stationary object that retains its spatial coordinates for a certain period of time and releases pollutants into the atmosphere. Stationary sources of combustion products in the oil and gas industry are: chimneys of boiler houses, thermal power plants; gas pumping units at compressor stations of main gas pipelines; technological flares at fields, gas and oil refineries, which are designed to burn emergency emissions from technological installations. Stationary sources of pollutants at the enterprises of the oil and gas complex are of average height h = 10 ÷ 50 m, diameter d= 1.5 m (Govdyak et al., 2007).

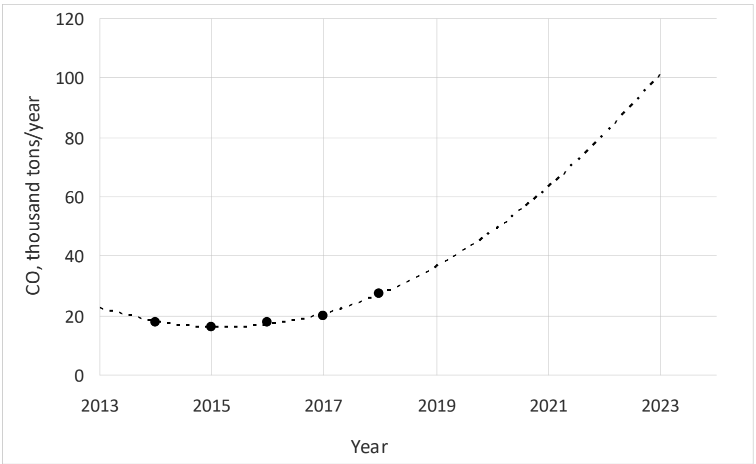


Fig. 2. Carbon monoxide emissions

Hazard criteria must be considered to predict atmospheric pollution. When using forecasting methods, it is necessary to determine in which cases the degree of concentration of harmful impurities in the air reaches certain critical values and how far the latter can be exceeded. Depending on the magnitude of this excess, guidance may be provided on quantifying the required emission reductions.

To simulate the dispersion of pollutants in the atmospheric air, it is necessary to take into account the parameters of the sources of contamination, the characteristics of the process of chemical transfer in the atmosphere, meteorological conditions, etc. The more accurate this data is, the more accurate the simulation results will be. However, not all of this data can be collected or reliable. Therefore, the choice of models for describing the dispersion of pollutants in the air must take into account both the conditions of the task and the amount of reliable input data to solve it.

The scheme of the model, shown in Fig. 3, is laid down in the calculations.

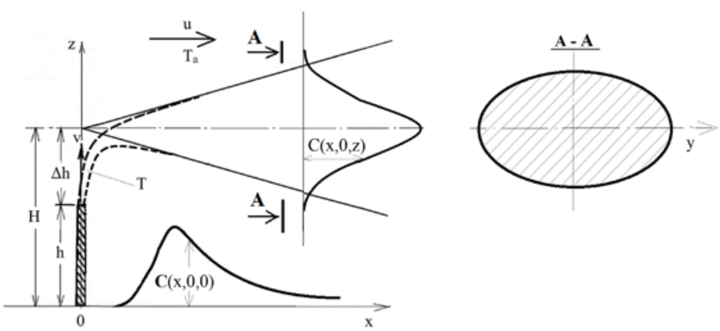


Fig. 3. The scheme of the model

With a weak wind, the smoke from the chimney first spreads almost vertically upwards, and only at a certain level does its movement acquire horizontal components. Therefore, the calculations need to consider some virtual source, the effective height *H* of which takes into account the initial rise of the jet, which depends on wind speed *u,* velocity emission *v* and flue gas temperature *T*.

The Gaussian model allows us to consider the steady state dispersion of contaminants. It is accepted that the meteorological parameters are unchanged. The Gaussian model is most commonly used to predict the proliferation of long-term atmospheric pollution from sources located at ground level or at some altitude. The application of the model is limited locally. The basic Gaussian dispersion equation can be written as follows (Beketov et al., 2011):

$$C_{(x,y,z,H)} = \frac{M}{2\pi u\sigma_y(x)\cdot\sigma_z(x)}\left[\exp-\left(\frac{y^2}{2(\sigma_y(x))^2}\right)\right]\cdot \\ \cdot\left[\exp-\left(\frac{(z-H)^2}{2(\sigma_z(x))^2}\right)+\exp-\left(\frac{(z+H)^2}{2(\sigma_z(x))^2}\right)\right], \quad (1)$$

where *C* is the concentration at some point with the coordinates *x, y, z*, g/m^3;

M – emission rate, g/s;

H – effective height of the source, m (height of the virtual source);

u – average wind speed at the height of the virtual emission source, m/s;

σ_y – standard deviation of horizontal dispersion, m;

σ_z – standard deviation of vertical dispersion, m;

y is the lateral deviation from the axis of the torch, m.

The Gaussian equation for determining the dispersion of contaminants is valid under the following assumptions:

1) jet dispersion in the horizontal and vertical planes is described by the Gaussian distribution with standard deviations of the concentration distribution σ_y and σ_z along the *y* and *z* axes, respectively;

2) the average wind speed *u* is constant at the effective height of the emission;

3) emission rate is constant;

4) there is a reflection of the jet from the surface of the earth.

The size of the toxic hazard zone for the emission of harmful substances depends on both the emission rate and the characteristics of the atmospheric transfer, above all, the wind speed and the category (class) of stability of the atmosphere. Atmospheric stability classes differ mainly in the intensity of vertical air mixing. There are six stability classes of the surface air layer: "A", "B", "C" are related to strong, moderate and weak instability, respectively; "D" — to an equilibrium state; "E" and "F" - to weak and moderate stability. To assess the dispersion of pollutant emissions, the most unstable class "A" was selected, which gives the worst characteristics in terms of pollution (Pasquill et al., 1983).

For the practical use of the above equation, in addition to the physical data (coordinates, emission rate, effective source height), it is also necessary to know the value of u, σ_y, σ_z.

In order to improve dependence (1) for determining the nature of the distribution of concentrations of pollutants, it is proposed to determine the wind speed and the effective height of the source by the formulas given in (Zannetti, 1990).

The wind speed at the effective height of the emission source is calculated as follows:

$$u = u_1 \left(\frac{h}{z_1} \right)^p , \tag{2}$$

where *h* is the geometric height of the emission source, m;

u_1 – near ground wind speed, m/s;

z_1 – height measurement of near ground wind speed (usually 10 m), m;

p – correction factor (selected from the table).

In the class of atmospheric stability, the average wind speed u_1 is 1.5 m/s, the coefficient *p* is 0.07 (Pasquill et al., 1983).

Effective source height (virtual source height), $H = h + \Delta h$,

where Δh – the initial rise of the jet.

The value Δh for source with circular hole is determined by the wind speed at the effective height of the emission source *u* and the emission characteristics by which the auxiliary value of F_b is calculated follows as:

$$F_b = gvd^2 \left(\frac{T - T_a}{4T} \right), \tag{3}$$

where *g* is the acceleration of gravity, m^2/s;

v – velocity of gas emission, m/s;

d – diameter of the hole source of the source of emissions, m;

T – temperature of gases, °C;

Ta is the ambient temperature, °C.

The initial jet rise is determined by this dependence:

$$H = h + 1{,}6 \frac{\sqrt[3]{F_b}}{u} , \tag{4}$$

where *u* is the wind speed at the effective height of the emission source, m/s.

The coefficient of lateral (transverse) diffusion σ_y characterizes the horizontal expansion of the jet in a direction perpendicular to the direction of motion. The vertical diffusion coefficient σ_z characterizes the expansion of the jet vertically. The values σ_y , σ_z (horizontal and vertical standard deviation) depend on the position of the point *X* in the wind direction from the source and on the conditions of stability of the atmosphere. The values σ_y , σ_z are determined according to the diagrams obtained experimentally.

Using experimental data (Berlyand, 1991), mathematical models were constructed to determine the coefficients of lateral and vertical diffusion in the stability class of the atmosphere "A".

The standard deviation of horizontal dispersion is determined by the following relationship:

$$\sigma_y = 0.2165 \cdot x + 4.1333 \cdot \tag{5}$$

The standard deviation of vertical dispersion is determined by the following relationship:

$$\sigma_z = 4.89744 \cdot 10^{-12} x^5 - 1.11603 \cdot 10^{-8} x^4 + 9.43263 \cdot 10^{-6} x^3 - 3.17008 \cdot 10^{-3} x^2 + 6.05501 \cdot 10^{-1} x - 2.08667 \cdot 10, \quad (6)$$

where x is the distance from the source of contamination.

3. Results and discussion

The dispersion character of carbon monoxide air pollutant is determined by dependence (1).

The height of the emission source is assumed to be 50 m, 30 m, 15 m, diameter –

1.5 m, gas outlet velocity 10 m/s, emission rate 46.3 g/s, gas temperature 400 ºC. Near ground wind speed 1.5 m/s.

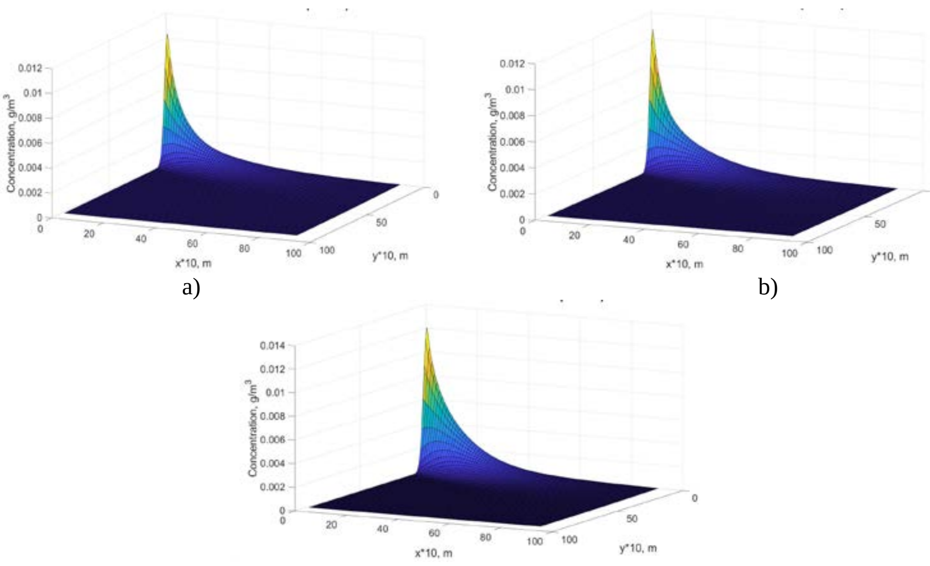
The concentration of carbon monoxide was calculated at z = 2 m, z = 100 m and $z = H$ for each source height h = 50m, 30 m and 15 m.

The results of the calculations are shown in Fig. 4 – 6

Fig. 4 shows the nature of the change concentration of pollutant emission at the level of effective height for 50 m, 30 m and 15 m source heights ($z = H$).

At the pollutant emission level $z = H$, the concentration is decreased by exponential law with increasing x. As x is grown, this decline is slowed. The bulk of the harmful substances is concentrated in a relatively narrow jet whose axis corresponds to y = 0. For example, at x = 0 the concentration of pollutants is 0.010412 g/m^3, at x = 100 m the concentration will be 0.0031251 g/m^3. The carbon monoxide concentration is approached zero at a distance of 900 m (Fig. 4a).

The maximum concentration is 0.010793 g/m^3 for a source with a height of 30 m (Fig. 4b) and C = 0.012107 g/m^3 for a source with a height of 15 m (Fig. 4c).



a) b)

c)

Fig. 4. The concentration of emission at the level of effective height H
a – height of the source h = 50 m
b – height of the source h = 30 m
c – height of the source h = 15 m

Consequently, the concentration is increased with decreasing source height. It was determined the excess concentration of carbon monoxide in the ambient air. The degree of air pollution is determined by the highest calculated value of the concentration, which corresponds to adverse meteorological conditions, dangerous wind speed.

For carbon monoxide, the maximum one-time MPC is 3 mg/m^3 (Semchuk et al., 2019). The maximum concentration exceeds the MPC 4 times for a source 15 m height. For a source 30 m height – 3.6 times and 50 m – 3.5 times.

The change in the concentration of pollutants depending on the height of the source at the level z = 2 m is shown in Fig. 5. For example, the maximum concentration C=0.0015668 g/m^3 will be at a distance x = 150 m for a source with a height of 50 m (Fig. 5a). The maximum concentration C=0.0040505 g/m^3 will be at a distance of x = 50 m for a source with a height of 30 m (Fig. 5b) and C = 0.01163 g/m^3 will be at a distance of x = 10 m for a source with a height of 15 m (Fig. 5c).

The most hazardous emission is observed for a source of contamination with a height of 15 m. The maximum concentration exceeds the MPC by 3.9 times for a source of contamination with a height of 15 m. The maximum concentration exceeds the MPC by 1.4 times for a source of contamination with a height of 30 m and is 0.5 MPC for a source 50 m height. This indicates that harmful pollutants will adversely affect the health of the service personnel.

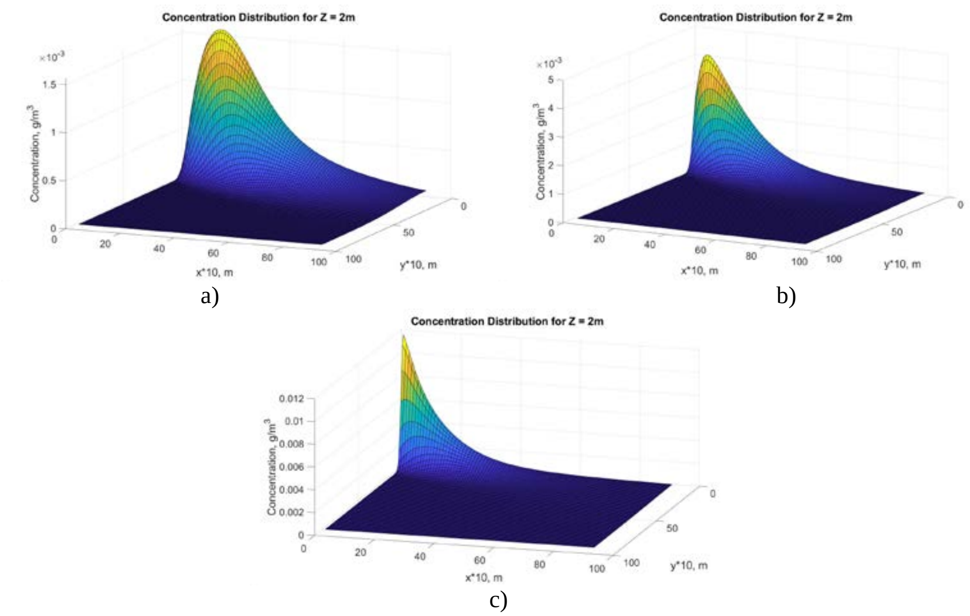
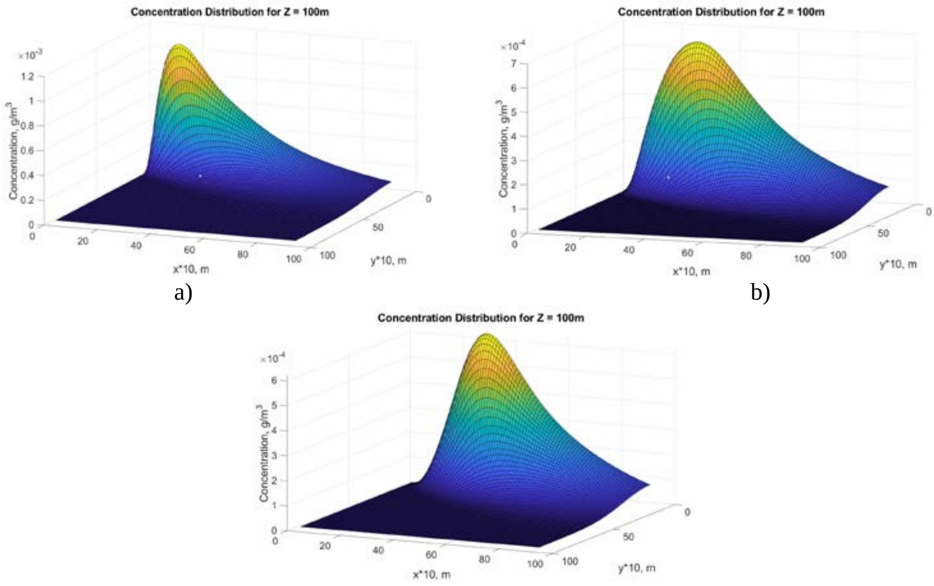


Fig. 5. The concentration of emission for z = 2 m
a – height of the source h = 50 m
b – height of the source h = 30 m
c – height of the source h = 15 m

It is interesting to know how the concentration at z = 100 m will be distributed for the three studied sources (Fig. 6). The maximum concentration is C=0.0010307 g/m^3 at a distance of 110 m for height of a source 50 m (Fig. 6a). The concentration is C=0.0006278 g/m^3 at a distance of 250 m for a source with a height of 30 m (Fig. 6b) and C=0.0006214 g/m^3 at a distance of 300 m for a source with a height of 15 m (Fig. 6c). The maximum concentration is 0.3 MPC for a source of contamination with a height of 50 m, 0.2 MPC for sources with a height of 30 m and 15 m.

The analysis of the figures confirms the asymmetry of the shape of the curves relative to point *X*, which corresponds to the maximum concentration of pollutants. The increase of concentration with distance is much stronger at $x < x_{max}$, where the concentration is maximum. The decrease of concentration is at $x > x_{max}$.



a) b) c)

Fig. 6. The concentration of emission for z = 100 m
a – height of the source h = 50 m
b – height of the source h = 30 m
c – height of the source h = 15 m

It should be noted that the oil and gas companies annually develop plans for integrated environmental measures, which include measures for the protection and use of water resources, the protection of atmospheric air, the protection and rational use of subsoil and land resources and waste management. While performing environmental work, the requirements of environmental legislation of Ukraine are observed. The requirements are aimed at minimizing the negative impact on the environment of the production activities of enterprises in the corporate management of the company.

4. Conclusions

Mathematical models were developed to determine the coefficients of lateral and vertical diffusion for the atmosphere stability class "A".

Emissions of pollutants into the atmosphere by stationary sources of different heights were analyzed, which will allow in the future when designing similar facilities to determine the optimal height of the source of pollution to minimize the impact of emissions on the health of service personnel.

It is possible to predict the concentration of harmful substances on the site during the emission of combustion products from the source of pollution of a certain height, if the expected values of wind speed, atmospheric stability and emission rate are known.

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