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DEVISING A PROCEDURE TO FORECAST THE LEVEL OF CHEMICAL DAMAGE TO THE ATMOSPHERE DURING ACTIVE DEPOSITION OF DANGEROUS GASES

This paper reports a procedure devised to forecast the level of chemical pollution of the atmosphere, which includes a mathematical model for the distribution of the concentration of dangerous gas in the atmosphere at its active deposition by dispersed jets of liquid, as well as a technique for its implementation. Based on the differential equations of gas distribution in space, a phased model of the propagation of a cloud of a dangerous chemical substance was built. The model describes stages in the discharge of a dangerous gaseous substance from emergency technological equipment, the deposition of dangerous gas by a finely-dispersed flow, and free propagation of the cloud in the air. The reported mathematical model makes it possible to calculate the size of pollution zones while determining the boundary safety conditions. When forecasting, the main meteorological parameters, the width of the deposition zone, and the chemical properties of both the gas and liquid are taken into consideration. The comparative analysis of the results of forecasting a conditional zone of chemical damage with the free propagation of the cloud, and at the active deposition by precipitation or technical devices, was carried out. The simulation results revealed that with an increase in the wind speed from 1 m/s to 5 m/s, the size of the affected area increases by 2.7 times, while the concentration of dangerous gas in the cloud falls by 2.5–3 times. An algorithm has been proposed for integrating the devised methodology of forecasting the level of chemical pollution of the atmosphere into a general cycle of emergency management. It should be especially noted that the devised procedure contains the entire range of components that are necessary for its practical application. It includes a description of the procedure and practical recommendations for the use of the proposed technique in the elimination of emergencies, as well as a list of probable events when the use of the developed procedure would be most effective

Keywords: dangerous gases, deposition of hazardous substance, forecasting of the scale of pollution, localization of the affected area

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1. Introduction

The current state of the industry requires the use of a large number of various chemicals. Even under the conditions of the normal operation of industrial enterprises, a large number of hazardous chemicals are emitted into the environment. The main environmental objects that are adversely affected by hazardous substances are air, water, and soil. Especially large-scale emissions occur in the event of large-scale accidents at such facilities. Despite considerable efforts to comply with the rules of safe operation at facilities and enterprises where hazardous chemicals are manufactured, stored, and used, emergencies do arise. Emergencies with the release of hazardous chemicals (HCs) are characterized by a significant size of the affected area, which can reach several square kilometers. An additional complication is a presence in the affected area of a large number of civilians and the need to attract significant forces and means to eliminate the consequences of such an emergency [1]. This poses a significant threat to the population, territory, and environment, which are the main objects of the civil protection system. In order to ensure environmental safety in the zone of atmospheric pollution with the release of hazardous gases and to take a managerial decision on the evacuation of the population, it is important to properly monitor and accurately forecast the evolution of an emergency [2]. Forecasting the development of an emergency is a mandatory stage for making a correct management decision on the elimination of an accident [3]. The forecasting process is especially important in the event of an emergency with the discharge of gaseous hazardous chemicals.

To ensure sufficient accuracy in calculating the size of chemical pollution zones, it is necessary to take into consideration a significant number of factors that can be conditionally divided into two blocks – meteorological conditions and emission parameters [4]. Meteorological conditions include wind direction and speed, temperature and humidity, atmospheric pressure. The parameters of discharge include the type of chemical, its temperature, density, storage pressure, and the intensity of emission [5]. Existing methods and means of preventing emergencies with the release of hazardous substances in the atmospheric air can influence the affected area at altitudes of several meters [6].

Existing global approaches to the elimination of the consequences of emergencies, which are characterized by the discharge into the atmospheric air of harmful and radioactive substances, are based on the use of liquid curtains with the help of ground rescue equipment. At the same time, there is a deposition of harmful and radioactive substances from atmospheric air by a finely-dispersed flow of water, which is created with the help of emergency and rescue equipment. In the presence of a deposition process in the emission zone, another block is added to those factors, which implies the intensity of the fluid flow for deposition, the deposition area, the presence of a chemical reaction of a liquid with a dangerous chemical substance, etc. All this significantly complicates operations by environmental safety control services and emergency-rescue units to eliminate atmospheric pollution.

Analysis of the main causes of accidents that occurred at chemically hazardous facilities (CHF) revealed that a significant cause of emergencies at chemically hazardous objects is the depressurization of various storage tanks for chemically hazardous substances [7]. A significant factor in the danger of atmospheric air is accidents at nuclear power plants, which lead to large sizes of the affected areas and significant human casualties [8]. The process of protecting the population and territories from atmospheric pollution consists of several mandatory stages such as monitoring the pollution zone, predicting the development of an accident, taking a management decision, and directly influencing the pollution zone [9]. However, each of these stages requires a separate construction of methods for their implementation.

Given this, a relevant issue that must be addressed is the lack of consideration of the active elimination of an accident by operational and rescue units when predicting the spread of HC emission.

2. Literature review and problem statement

Every year there are more than 20 accidents at chemically hazardous enterprises in the world [10]. Analysis of the main causes of accidents that occurred at chemically hazardous facilities showed that the most significant cause of accidents is the human factor, namely personnel error. However, along with this, a significant cause of emergencies at chemically hazardous objects is the depressurization of various containers for storing chemically hazardous substances [11]. Such accidents lead to large sizes of the affected areas and, as a result, significant human casualties [12]. At the same time, work [13] shows that in industrialized countries there are several hundred enterprises where chemically hazardous substances are used. Despite the development of technologies to improve environmental safety at such enterprises [14], in the event of accidents, they may release dangerous chemicals. The total amount of chemically hazardous substances (HCs) at these enterprises exceeds 283 thousand tons, most of which are ammonia, chlorine, and sulfuric acid [15]. In addition, ammonia and chlorine under normal conditions are in a gaseous state and easily propagate in the atmosphere [16]. However, there are unresolved issues related to ensuring security at enterprises where HCs are used.

The elimination of accidents at CHF should include the mandatory stages of the crisis management circuit – monitoring, forecasting, management decision-making, and direct impact on the accident [17]. Among the main types of impact on an emergency, the greatest efficiency was demonstrated by ways to protect against the negative impact and to minimize the negative consequences of an accident [18]. At the same time, the accuracy of forecasting the evolution of an emergency directly affects the correctness of the management decision.

The mathematical modeling of the propagation of hazardous chemicals in the atmosphere involves a mathematical model of the diffusion of a substance in the air using a differential equation of the parabolic type [19]. Such models have proven effective when describing the processes of propagation of thermal destruction products [20]. Models of gas scattering from a point source belong to the Gaussian class, the main of which is the Pasquill-Gifford model [21]. The Gaussian model of impurities dispersion underlies IAEA procedures [22], which set out recommendations for determining dispersions based on input meteorological parameters and for performing calculations on emission dissipation after accidents at nuclear power plants. The model is characterized by a straight cloud trajectory and is intended for express accident assessments at relatively short distances [23].

The possibility of automatic application of the chemical contamination zone is provided in the WISER software package (USA) [24]. However, the disadvantage of that suite is to determine the size of the affected areas according to tabular reference data without the calculation process and without taking into consideration the main factors. It is possible to significantly improve the accuracy of forecasting by using the ALOHA software package (USA) [25]. That suite simulates the propagation of a dangerous substance using the Gaussian model of admixture dispersion [26] according to the parameters introduced and makes it possible to visualize the results of forecasting. However, the approaches reported in [20–26] do not take into consideration the deposition of a cloud of dangerous gases by operational and rescue units.

The deposition of a cloud of gaseous HC makes it possible to significantly reduce the size of the pollution zone [27], and, under certain conditions, to stop the spread of dangerous gases altogether [28]. However, paper [29] defines only the effect of the intensity of water supply on the precipitation of the cloud, without taking into consideration the dispersion of the flow. However, optimizing the dispersion of water flow can almost halve the deposition time of a hazardous substance [30]. It is possible to achieve an additional increase in the intensity of deposition of hazardous gases from the air through chemical additives to water, which increases the rate of gas sorption and neutralizes it [31]. Those factors must be taken into consideration when simulating the processes of deposition of dangerous gases.

The processes of deposition of gaseous substances from the atmosphere are based on the processes of interphase mass exchange [32]. The kinetics of gas absorption by liquid aerosols are quite complex and multifactorial. There are several fundamentally different approaches to solving this problem. Those approaches differ in the level of accuracy of the solution, the amount of time spent, the amount of input data, and the need for previous experimental studies. At the same time, there are two different approaches to model construction – the kinetic multilayer model for gas-particle (KM-GAP) [33] and the molecular dynamics (MD) simulation model [34]. The MD model is implemented on a special computer calculation platform GROMACS with an additional add-on for the calculation of absorption with liquid aerosols TIP4P-Ew [35].

However, no general mathematical model describing the propagation of a gaseous HC and its deposition during the elimination of an emergency has been built.

Thus, an unresolved issue is the lack of tools for predicting zones of chemical damage by gaseous substances with their active precipitation by natural precipitation or technical means.

3. The aim and objectives of the study

The purpose of this work is to devise a methodology for predicting the level of chemical damage to the atmosphere with the active deposition of dangerous gases. This would make it possible to improve the accuracy of assessing a dangerous situation in the accident zone, which could lead to an increase in the safety of rescuers and the effectiveness of emergency elimination.

To accomplish the aim, the following tasks have been set:

– to construct a mathematical model for the distribution of hazardous chemicals, taking into consideration the factors of their active deposition on the way of propagation;

– to devise a procedure for the practical use of the constructed mathematical model in predicting the level of chemical damage to the atmosphere.

4. The study materials and methods

The subject of this study is the process of deposition of gaseous substances by a finely-dispersed liquid flow. The study's object is dangerous gaseous substances in the atmosphere.

When describing the processes of propagation and deposition of gaseous substances, we shall proceed from the following assumptions:

1. HC is discharged from a point hole during the depressurization of a technological apparatus.
2. The depressurization of a technological apparatus occurs instantly, so the intensity of HC emission in time can be described by a stepped function.
3. The propagation of HC in the air occurs by diffusion and wind transfer. At the same time, the diffusion coefficient is the same, both horizontally and vertically.
4. Fluctuations in the wind speed in all directions are insignificant in comparison with the scale of emission and accuracy of forecasting; hence, they can be neglected.
5. The intensity and dispersity of water supplied for deposition are the same at all points of the deposition volume and do not change over time.
6. The flow of water for the deposition of HCs is fed to the entire depth of the cloud and throughout the height of the cloud.
7. The size of HC molecules is negligibly small compared to the size of water droplets.
8. The speed of the fall of water droplets is negligibly low compared to the velocity of movement of HC molecules.
9. During a flight through the HC cloud, a drop of water does not have time to absorb enough HCs to achieve equilibrium, so the rate of desorption of HCs would be negligible compared to the absorption rate.

To simulate the processes of diffusion of a dangerous chemical in the air, we used methods from the theory of differential equations in partial derivatives of the parabolic type. Such processes have already been described in detail in [19, 21].

$$\frac{\partial q}{\partial \tau} = D\left(\frac{\partial^2 q}{\partial x^2} + \frac{\partial^2 q}{\partial y^2} + \frac{\partial^2 q}{\partial z^2}\right) - v_x \frac{\partial q}{\partial x} -$$
$$- v_y \frac{\partial q}{\partial y} - v_z \frac{\partial q}{\partial z} + E\delta(x)\delta(y)\delta(z - z_0), \qquad (1)$$

where E is the intensity of the release of a substance, kg/s, which occurs at the point $(0, 0, z_0)$, S is the intensity of HC deposition with water curtains; $q(x, y, z, t)$ is the concentration of HCs in the air, kg/m^3; D is the diffusion coefficients in horizontal and vertical directions; v_x, v_y are the horizontal components of the vector, which determines the direction and speed of wind, m/s, v_z is the vertical component of wind speed, due to the category of stability of the atmosphere and the density of HCs.

On the surface of the earth, there is a boundary condition of the second kind:

$$\left.\frac{\partial q}{\partial z}\right|_{z=0} = 0, \qquad (2)$$

while the initial condition

$$q(x, y, z, 0) = 0, \qquad (3)$$

meets the absence of a substance in the air before emitting.

At a constant emission value E, the solution to problem (1) to (3) takes the form

$$q_1(x,y,z,\tau)=\frac{E}{8\pi^{3/2}D^{3/2}}\times \frac{1}{(\tau-t)^{3/2}}\exp\left[-\frac{\left(x-v_x(\tau-t)\right)^2+\left(y-v_y(\tau-t)\right)^2}{4D(\tau-t)}\right]\times$$
$$\times\int_0^{\tau}\times\left\{\begin{aligned}&\exp\left[-\frac{\left(z-v_z(\tau-t)-z_0\right)^2}{4D(\tau-t)}\right]+\\&+\exp\left[-\frac{\left(z-v_z(\tau-t)+z_0\right)^2}{4D(\tau-t)}\right]\end{aligned}\right\}\mathrm{d}t, \qquad (4)$$

We solved the equations by numerical methods. To this end, the mathematical software package MAPLE (Canada), version 18, was employed. The input parameters selected for the numerical calculation of the distribution of gas concentration in the air were the average characteristics of the sprayed flow of liquid formed by emergency and rescue equipment. These characteristics include the height of the jet supply, to 10 m; the distance to which the jet is supplied, to 20 m; the average dispersity of the drop stream, 1 mm.

5. Results of devising a methodology for predicting the level of chemical damage to the atmosphere during the active deposition of dangerous gases

5. 1. Building a model for the propagation of hazardous gases in the atmosphere during their active deposition

In order to simplify the mathematical notation, it is proposed to consider the process of propagation and deposition of hazardous gases in the atmosphere as a chain of stage-to-stage simple processes (Fig. 1).

At the first stage, the process of free gas propagation in the atmosphere is modeled after its discharge from a technological apparatus (1) to (4). In this case, determining factors are diffusion coefficients in horizontal and vertical directions; horizontal components of the vector, which defines the direction and speed of the wind; a vertical component of wind speed, due to the category of stability of the atmosphere and the density of HCs.

The results from the calculation at the boundary of the first stage are the input parameters for simulating the second stage.

At the second stage (Fig. 1), there is a deposition of a dangerous gas from the atmosphere with an aqueous aerosol supplied from stationary or mobile devices. At the same time, the condition is accepted that the parameters of the water aerosol are the same throughout the washing area. The intensity of washing out dangerous gas from the atmosphere is affected by the coefficient of gas accommodation on the surface of the liquid; the volume concentration of water droplets; the average radius of water droplets in the jet; a Henry's constant (chemical composition of dangerous gas); temperature.

When building a model of deposition of dangerous gas, we propose the introduction of a coefficient β, which takes into consideration the rate of absorption of gas by a drop of liquid. Considering this, the rate of deposition of HCs can be represented in the form:

$$S=\beta q(x,y,z,\tau), \qquad (5)$$

where

$$\beta=\frac{\alpha DCr}{HR_0T},$$

where α is the coefficient of gas accommodation on the surface of the liquid; C is the volumetric concentration of water droplets, m^{-3}; r is the average radius of water droplets in the jet, m; H is the Henry's constant, mol/(Pa·m^3); R_0 is the universal gas constant, J/(mol· K); T – temperature, K.

Then the equation of diffusion in the area of active deposition takes the form:

$$\frac{\partial q}{\partial \tau}=D\left(\frac{\partial^2 q}{\partial x^2}+\frac{\partial^2 q}{\partial y^2}+\frac{\partial^2 q}{\partial z^2}\right)-v_x\frac{\partial q}{\partial x}-$$
$$-v_y\frac{\partial q}{\partial y}-v_z\frac{\partial q}{\partial z}-\beta q(x,y,z,\tau), \qquad (6)$$

under the initial condition

$$q(x,y,z,0)=0, \qquad (7)$$

the boundary condition of the second kind on the surface of the earth

$$\left.\frac{\partial q}{\partial z}\right|_{z=0}=0, \qquad (8)$$

and the boundary condition of the first kind on the border where cooling begins:

$$q(0,y,z,\tau)=q_1(x_1,y,z,\tau), \qquad (9)$$

where q_1 is the concentration of matter (4), obtained as a solution to problem (1) to (3).

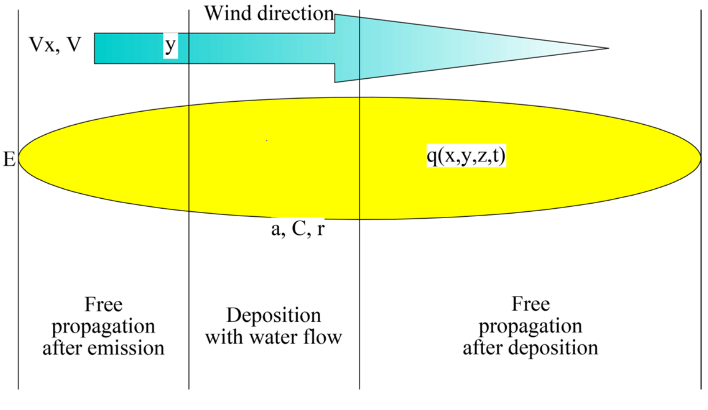


Fig. 1. Simulation scheme of the propagation process of dangerous gas with active deposition

In problem (6) to (9), we replaced

$$q(x,y,z,\tau)=\exp\left(A_1x+A_2y+A_3z+B\tau\right)u(x,y,z,\tau), \qquad (10)$$

where $A_1=\frac{v_x}{2D}$; $A_2=\frac{v_y}{2D}$; $A_3=\frac{v_z}{2D}$; $B=-\beta-\frac{1}{4D}\left(v_x^2+v_y^2+v_z^2\right)$. Then equation (3) is converted to

$$\frac{\partial u}{\partial \tau}=D\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right). \qquad (11)$$

The initial condition remains unchanged

$$u(x,y,z,\tau)=0, \qquad (12)$$

while the boundary ones take the form

$$u(0,y,z,\tau)=q_1(x_1,y,z,\tau)\exp\left(-A_2y-A_3z-B\tau\right), \qquad (13)$$

$$\left.\left(A_3u+\frac{\partial u}{\partial z}\right)\right|_{z=0}=0. \qquad (14)$$

A solution to boundary problem (11) to (14) is as follows

$$\begin{aligned} u=&D\int_0^{\tau}\mathrm{d}t\int_{-\infty}^{\infty}\mathrm{d}\eta\times\\ &\times\int_0^{\infty}\left.\begin{matrix}\mathrm{d}\zeta q_1(x_1,\eta,\zeta,t)\exp(-A_2\eta-A_3\zeta-Bt)\times\\ \times\frac{\partial G}{\partial \xi}(x,y,z,\xi,\eta,\zeta,\tau-t)\end{matrix}\right|_{\xi=0}, \end{aligned} \qquad (15)$$

where G is the Green's function in problem (11) to (14):

$$\begin{aligned} &G(x,y,z,\xi,\eta,\zeta,\tau)=\\ &=\frac{1}{8(\pi D\tau)^{3/2}}\left\{\begin{matrix}\exp\left[-\frac{(x-\xi)^2}{4D\tau}\right]-\\ -\exp\left[-\frac{(x+\xi)^2}{4D\tau}\right]\end{matrix}\right\}\times\\ &\times\left\{\exp\left[-\frac{(y-\eta)^2}{4D\tau}\right]\right\}\times\\ &\times\left\{\begin{matrix}\exp\left[-\frac{(z-\zeta)^2}{4D\tau}\right]+\\ +\exp\left[-\frac{(z+\zeta)^2}{4D\tau}\right]+\\ +2A_3\sqrt{\pi D\tau}\exp\left[k^2D\tau-A_3(z+\zeta)\right]\times\\ \times erfc\left(\frac{z+\zeta}{2\sqrt{D\tau}}-A_3\sqrt{D\tau}\right)\end{matrix}\right\}. \end{aligned} \qquad (16)$$

Then the concentration of HCs in the active deposition area is to be determined by expressions (10), (15), (16).

The third stage is the arbitrary propagation of dangerous gas left in the atmosphere after the deposition of a dangerous cloud.

$$q(x,y,z,\tau)=\exp\begin{pmatrix}M_1x+M_2y+\\ +M_3z+N\tau\end{pmatrix}w(x,y,z,\tau), \qquad (19)$$

where $M_1=\frac{v_x}{2D}$;

$M_2=\frac{v_y}{2D}$;

$M_3=\frac{v_z}{2D}$;

$N=-\frac{1}{4D}\left(v_x^2+v_y^2+v_z^2\right)$;

$$\begin{aligned} &w=\\ &=D\int_0^{\tau}\mathrm{d}t\int_{-\infty}^{\infty}\mathrm{d}\eta\times\\ &\times\int_0^{\infty}\left.\begin{matrix}\mathrm{d}\zeta q_2(x_1,\eta,\zeta,t)\exp(-M_2\eta-M_3\zeta-Bt)\times\\ \times\frac{\partial G}{\partial \xi}(x,y,z,\xi,\eta,\zeta,\tau-t)\end{matrix}\right|_{\xi=0}, \end{aligned} \qquad (20)$$

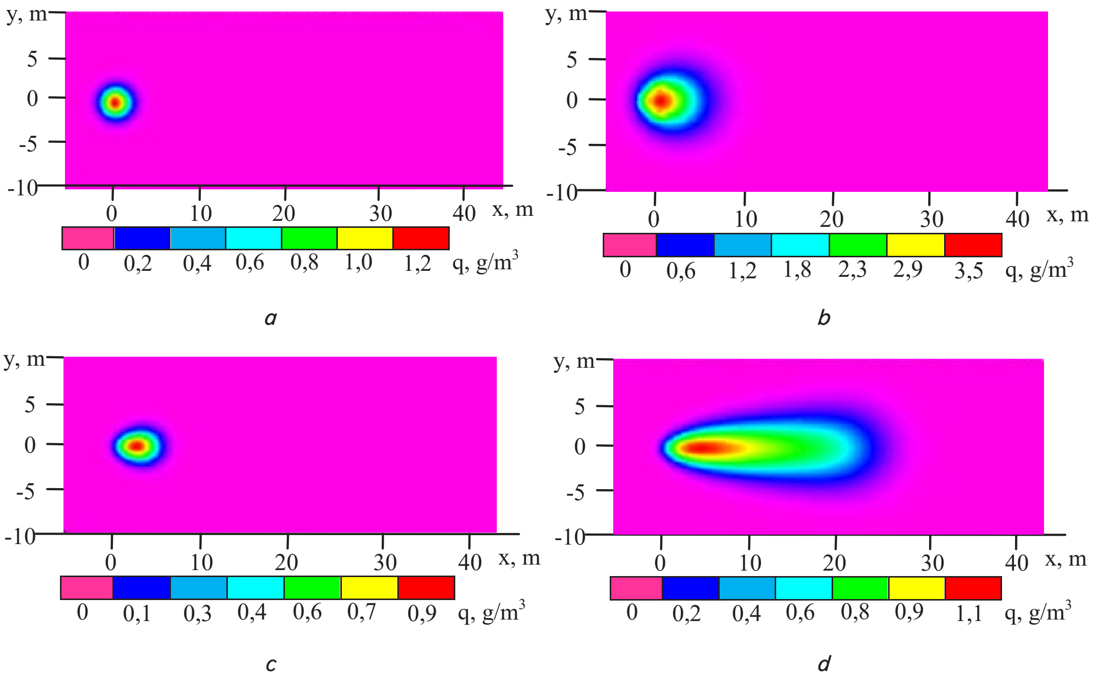
$$\begin{aligned} &G(x,y,z,\xi,\eta,\zeta,\tau)=\\ &=\frac{1}{8(\pi D\tau)^{3/2}}\times\\ &\times\left\{\begin{matrix}\exp\left[-\frac{(x-\xi)^2}{4D\tau}\right]-\\ -\exp\left[-\frac{(x+\xi)^2}{4D\tau}\right]\end{matrix}\right\}\times\\ &\times\left\{\exp\left[-\frac{(y-\eta)^2}{4D\tau}\right]\right\}\times\\ &\times\left\{\begin{matrix}\exp\left[-\frac{(z-\zeta)^2}{4D\tau}\right]+\\ +\exp\left[-\frac{(z+\zeta)^2}{4D\tau}\right]+\\ +2M_3\sqrt{\pi D\tau}\exp\left[k^2D\tau-M_3(z+\zeta)\right]\times\\ \times erfc\left(\frac{z+\zeta}{2\sqrt{D\tau}}-M_3\sqrt{D\tau}\right)\end{matrix}\right\}. \end{aligned} \qquad (21)$$

The resulting system of equations (4), (10), and (19) makes it possible to determine the boundaries of pollution zones with hazardous chemicals during their active deposition with sprayed jets.

We tested the feasibility of our model using the MAPLE mathematical software package (Canada). In this case, the sequence of stages in the free distribution and deposition of an HC cloud was determined in advance. When predicting, the condition was accepted that the results of the calculation at the preliminary stage are the initial data for the next stage.

Fig. 2 shows forecasting results for a cloud of hazardous gas at height z=2 m at different times.

A criterion selected to attribute to the cloud is the concentration distribution of the substance in the air. At the same time, the average horizontal wind speed v_x was variable; vertical component, v_z=0.005 m/s. The calculations were performed for the coefficient of turbulent diffusion D=1 m^2/s; the height of the source z_0=2 m; emission source intensity E=0.1 kg/s.



a *b* *c* *d*

Fig. 2. The results of forecasting the size of the zone of propagation of hazardous gases in the air at different values of horizontal wind speed vx: *a* – vx=1 m/s, t=1 s; *b* – vx=1 m/s, t=5 s; *c* – vx=5 m/s, t=1 s; *d* – vx=5 m/s, t=5 s

5. 2. Devising a procedure for the practical use of the mathematical model in predicting the level of chemical damage to the atmosphere

When devising a methodology for predicting the level of chemical damage, it is necessary to adhere to the principles of step-by-step actions and interlevel direct and reverse links. At the same time, different services and performers can be responsible for each individual stage; however, their interaction is coordinated by the general operational and rescue headquarters.

5. 2. 1. Substantiating ways to acquire initial data for forecasting

The first stage in the procedure is to monitor an emergency zone. The emergency monitoring structure consists of three levels [36]. The first level includes devices for registering dangerous factors or meteorological parameters. Such devices can be used both to register one parameter and several parameters in parallel. Since the control of parameters must be carried out at different points in space, the control devices can be spaced horizontally (at points with different geographical coordinates) and vertically (control of parameters at different heights).

The primary information obtained by means of controlling parameters using cables or radio channels is transmitted to second-level devices, which are intended to process the information received and provide it to the third level in a convenient form. At the third level, the information received is analyzed and a decision is made on further actions to eliminate the emergency.

Given the development of communication and telecommunication technologies, it is possible to combine monitoring systems of several states, thus creating a global monitoring system at the international level [37]. With the increase in the level of the monitoring system, the structure of the construction of the system is significantly complicated, namely the subsystems of processing, analysis, and systematization of information. There are two approaches to the construction of monitoring systems at regional, state, and international levels [38]. The first includes the development of a technical base, which is immediately focused on monitoring the zone of large size. Such systems primarily include satellite monitoring systems. The second approach implements the principle of combining and systematizing data from object-level monitoring devices. The extensive network of such control devices makes it possible to build a monitoring system at the regional and state levels.

In addition to level gradation, monitoring systems can be divided according to the basic principles of information acquisition.

The first class of systems includes remote sensing spacecraft [39].

Remote sensing of the Earth using artificial satellites provides the ability to obtain information about the ecological and meteorological state of the pollution zone and the surrounding area on a global scale with a high level of space-time recognition. At the same time, the physical, chemical, biological, and geometric parameters of the monitoring zone are controlled [40].

In Europe, the development of satellite monitoring systems is carried out in the countries of the European Union and in the Russian Federation under the GMES program, which uses the Envisat and Metop satellites. Satellite monitoring of the meteorological situation on the planet is carried out in order to detect the speed and direction of wind, humidity, and temperature [41].

In the field of development and use of space means of atmospheric monitoring, the United States of America occupies a leading position. The United States has implemented a satellite meteorological system, which is part of the NOAA (National Oceanic Atmospheric Administration) program and has NOAA satellites and geostationary satellites GEOS in polar orbits. The Canadian monitoring system uses Radarsat satellites [42].

In addition, the U.S. Department of Defense launched the DMSP satellite meteorological system (Defense Meteorological Satellite Project). The use of microwave radiometers in the DMSP system as all-weather meters of atmospheric parameters makes it possible to implement round-the-clock monitoring of hydrometeorological phenomena of WMO member countries (World Meteorological Organization).

In addition, the U.S. government decided to create a National Polar-Orbiting Operational Environment Satellite System (NPOESS) [43]. This system coordinates the work of military (DMSP) and civilian (NOAA) satellite systems and includes research satellites "Wind", "Coriolis", "Terra", "Aqua" [44].

Due to the strict mass-sized restrictions of artificial Earth satellites (AES), the functions of analyzing the information obtained have been transferred to the ground segment of the general monitoring system.

It should be noted that space monitoring systems have a number of significant shortcomings in relation to the elimination of the consequences of emergencies. Most often, this is the inability to find a satellite directly above the emergency zone in the required period, the significant impact of cloud cover on the monitoring results, a narrow range of measurable parameters, and low measurement accuracy by height above Earth level.

The use of ground monitoring systems makes it possible to eliminate the shortcomings of space monitoring systems. In addition, the application of such systems has a significant economic advantage during the operation of the equipment.

These complexes are designed in different countries. Siemens Plessey 45C radar is used in the UK. In Germany, DWD radars are used. There are also Italian-made MRL ("ALENIA-SMA" and "EEC-ERICSSON") and those manufactured in Japan ("Mitsubishi" brand) [45].

The most effective means of monitoring a pollution zone and the meteorological situation, which make it possible to eliminate the shortcomings of the space and ground monitoring systems, are aircraft. In this case, unmanned aerial vehicles (UAVs) are the most promising.

Unmanned aerial vehicles (UAVs) have the greatest potential among monitoring tools [46]. Devices of this type can carry up to 10 kg of payload, which makes it possible to use a fairly wide range of control and measuring equipment. The carrying capacity of a helicopter-type UAV is higher than the aircraft's and reaches five tens of kilograms of payload. That makes it possible to utilize a powerful instrument base. For the purposes of monitoring chemical pollution, compact lidar systems can be used. Lidar assemblies are equipped with a set of emitters in a wide spectral radiation range (from ultraviolet to far-infrared).

An aerosol lidar determines the location and tracks the evolution of natural and artificial aerosol formations in the atmosphere, as well as estimates the characteristic size of particles. A polarizing lidar investigates their aggregate state and physical structure (solid or liquid). DIAL measures the concentration of iodine isotopes in the atmosphere, which can be used to control the level of radiation contamination. A lidar that measures air turbulence makes it possible to predict the direction and speed of the spread of the cloud of pollution. The use of an infrared lidar makes it possible to determine a zone of burning in the case of the elimination of natural fires. To more accurately determine the chemical nature of dangerous gases, one can use the Fourier spectrometer.

5. 2. 2. Integrating the procedure of forecasting the level of chemical damage to the atmosphere into the general system of civil protection

Once we analyze the components of the methodology for predicting the level of chemical damage to the atmosphere during the active deposition of hazardous gases, we can come to the conclusion that this procedure is an integral part of the general cycle of crisis management (Fig. 3).

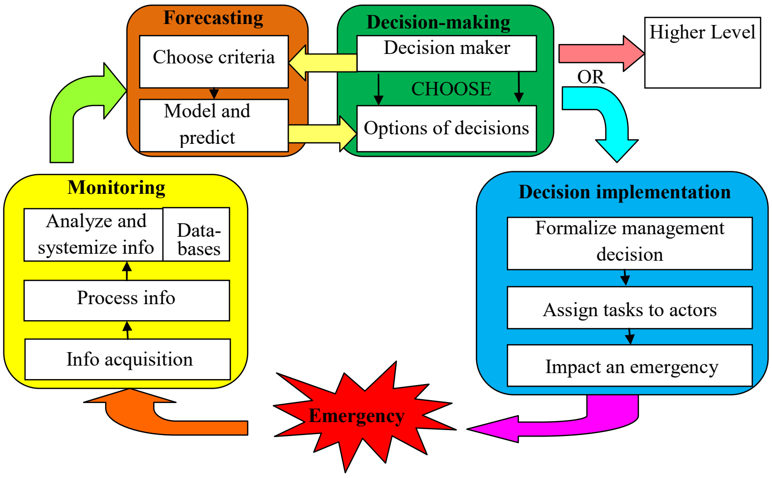


Fig. 3. Structure of crisis management in the elimination of an accident

Fig. 3 shows that the first two blocks of the crisis management cycle are entirely related to the forecasting method. The choice of defining criteria by which the forecasting is carried out is made by a separate person or collective body with governing powers. That is, the governing body determines under what conditions and at what time the accident is being predicted. An effective approach is the simultaneous forecasting of several options for the development of the situation. That allows the governing body to assess the consequences of various management decisions and choose the best solution. Next, the governing body sets tasks for responding to an accident to the performers, given the availability of appropriate resources. Premature and high-quality forecasting of the consequences of an accident makes it possible to determine in advance the needs for people's resources, technical and material resources. If necessary, the governing body may request additional resources from the senior management.

After active impact on the emergency zone, the input parameters for the next stage of forecasting change. Therefore, monitoring the emergency zone is continuous during the entire process of elimination of the consequences of the accident. The next stage of forecasting the development of an accident with updated monitoring data makes it possible for the manager to assess the correctness of management decisions and the quality of the tasks assigned to the rescue services. If necessary, the elements of emergency response are adjusted.

6. Discussion of results of devising the methodology for predicting the level of chemical damage to the atmosphere

Our results from numerical modeling (Fig. 2) indicate that the proposed mathematical model makes it possible to calculate the distribution of the concentration of hazardous gases in the atmosphere under different conditions. Fig. 2 shows that with an increase in the wind speed from 1 m/s to 5 m/s, the size of the affected area increases by 2.7 times, while the concentration of dangerous gas in the cloud falls by 2.5–3 times.

The derived equations (4), (10), and (19) can be used for two types of forecasting – preliminary and emergency.

Preliminary forecasting is carried out before the emergency discharge of dangerous gases. The conditions for such forecasting are the most likely conditions of a hypothetical accident. Pre-forecasting is used both for engineering and emergency planning purposes.

In engineering design, preliminary forecasting is used to determine the required intensity of water curtains at the exits from the premises where hazardous substances are manufactured, stored, and used. An example of such design is the design of a warehouse for storing chlorine at water treatment plants.

In addition, preliminary forecasting is used to determine the safe distances of building chemically hazardous objects, the norms of building residential buildings in an industrial area, and the location of technological premises on the territory of an enterprise.

Another area of application of long-term forecasting of the size of the chemical pollution zone is the preparation of emergency response plans for various rescue services. Typically, special civil protection departments in local authorities are engaged in drawing up such a plan. Such plans are then agreed upon with all emergency services that can be involved in the elimination of the consequences of an emergency. Such a plan is a guiding document for the emergency headquarters in the organization of interactions between different units in the emergency zone.

Emergency forecasting is carried out to promptly predict the development of an accident that has already occurred. The initial conditions for such forecasting are the monitoring data collected during the exploration of the accident site (Fig. 3). Emergency forecasting is carried out by employees of the operational headquarters at the scene of the accident. The equations (4), (10), and (19) are used to determine the number of rescue units that need to be used to deposit a cloud of dangerous gas and the safe distances of rescuers in the accident zone. For the civilian population, the calculation results (Fig. 2) are used to determine the number of personnel and the population requiring prompt evacuation.

The proposed methodology makes it possible to improve the efficiency and convenience of work of the headquarters for the elimination of emergencies and the safety of rescuers in the area of emission of hazardous substances. In addition, the suggested procedure makes it possible to plan in advance the evacuation of the population, which may face dangerous conditions.

It should be noted that the suggested procedure for predicting the level of chemical damage to the atmosphere during the active deposition of hazardous gases has a significant limitation, which is due to the assumption of complete overlapping of the cloud with water jets. That is, the use of the devised procedure is advisable for clouds with a width of up to 20 meters and a height of no more than 10 meters, which corresponds to the characteristics of jets from rescue equipment. The disadvantage of the built model is the impossibility of its correct use for larger clouds. To eliminate this disadvantage, our further studies should focus on the fragmentation of the affected area into separate areas with different deposition conditions.

7. Conclusions

1. The mathematical model that we constructed for the distribution of hazardous gas in the atmosphere with its active deposition with water aerosols makes it possible to improve the accuracy of calculations of gas concentration distribution in the atmosphere during the operation of stationary and mobile aerosol deposition systems. The mathematical model built is a system of three equations. The first equation describes the process of free gas propagation after emission from technological equipment. The second equation describes the process of deposition of gas from the atmosphere with a finely-dispersed liquid flow with different intensities. The third equation describes the process of free dispersion of gas in the atmosphere after deposition. With the help of computer modeling, the performance of the constructed mathematical model has been tested. The results of the numerical calculation showed that the greatest impact on the distribution of gas concentration in the atmosphere is exerted by wind speed, that is, with an increase in the wind speed from 1 m/s to 5 m/s, there is an increase in the size of the affected area by 2.7 times, while the concentration of dangerous gas in the cloud falls by 2.5–3 times.

2. We have devised a procedure to forecast the level of chemical damage to the atmosphere during the active deposition of hazardous gases to monitor determining the input parameters, the mathematical apparatus for calculating the concentration distribution of dangerous gases, as well as a procedure for the practical implementation of the constructed method of forecasting in the general civil protection system. Based on the characteristics of jets, which can be obtained with the help of rescue equipment, the use of the devised procedure is advisable for clouds with a width of up to 20 meters and a height of no more than 10 meters. A multi-level monitoring system has been proposed, which includes technical elements of data collection, processing, and transmission. Integrating the proposed methodology into the general management structure in the elimination of emergencies makes it possible to assess the danger under real conditions of localization of the emission. Improving the accuracy and efficiency of hazard assessment with the help of the proposed methodology could improve the safety of rescuers in the accident zone and organize the evacuation of the population from the emergency zone in advance.

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