12. Mardani, M., Mofidi, A. abbas, Ghasemi, A. (2015). A Credit Approach to Measure Inherent Hazards Using the Fire, Explosion and Toxicity Index in the Chemical Process Industry: Case Study of an Iso-max Unit in an Iran Oil Refinery. Caspian Journal of Health Research, 1 (1), 1–17. doi: https://doi.org/10.18869/acadpub.cjhr.1.1.1
13. Şakar, C., Zorba, Y. (2017). A Study on Safety and Risk Assessment of Dangerous Cargo Operations in Oil/Chemical Tankers. Journal of ETA Maritime Science, 5 (4), 396–413. doi: https://doi.org/10.5505/jems.2017.09226

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DEVELOPMENT OF MATHEMATICAL MODELS OF GAS LEAKAGE AND ITS PROPAGATION IN ATMOSPHERIC AIR AT AN EMERGENCY GAS WELL GUSHING

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Дослідження присвячено розробці нових математичних засобів для визначення розподілу в просторі та часі техногенного навантаження на атмосферне повітря в результаті непалаючого фонтанування газової свердловини. На сьогоднішній день моделювання є єдиним інструментом дослідження та вирішення актуальних задач екологічної безпеки експлуатації газоконденсатних родовищ. Особливо це стосується тих питань, відповіді на які неможливо отримати на практиці, а саме дослідження причин та прогнозування розвитку аварій з малою ймовірністю виникнення, але з великими руйнівними наслідками. Відзначено недоліки існуючих математичних моделей та методик, що не дозволяє їх використання для моделювання забруднення атмосфери саме при непалаючому фонтануванні газової свердловини. Задача прогнозування рівня та розподілу забруднення атмосферного повітря при відкритому фонтануванні газової свердловини включає два етапи: визначення обсягів газових викидів, їх параметрів і складу; розрахунок розсіювання шкідливих речовин в приземному шарі атмосфери. Досліджено фізичні особливості руху газової суміші по свердловині та розповсюдження домішок в атмосферному повітрі при непалаючому фонтануванні. Розроблено математичні моделі усталеного та залпового витікання суміші газів з свердловини у вигляді диференціальних рівнянь з відповідними початковими та граничними умовами. Дані моделі враховують всі основні фактори, що впливають на інтенсивність викиду газової суміші при аварійному фонтануванні, та адекватно описують даний процес. Розроблено нову математичну модель розповсюдження забруднюючих речовин в атмосферному повітрі при викиді з свердловини. Дана модель, на відміну від існуючих, представляє собою набір трьох аналітичних залежностей, що описують розповсюдження забруднюючих речовин в просторі та часі відповідно при залповому, короткочасному та неперервному викидах. Здійснено порівняння результатів математичних обчислень з даними натурних вимірювань концентрації забруднюючих речовин, що входили до складу аварійного викиду під час фонтанування газової свердловини газоконденсатного родовища Полтавської області. Визначено, що похибка моделювання не перевищує 15 % для всіх досліджуваних речовин. Це свідчить про високу адекватність розроблених моделей і можливість їх застосування для розв'язання більш широкого (в порівнянні з аналогами) класу задач, пов'язаних із контролем стану атмосферного повітря на територіях розташування газових свердловин за різних умов викидів, метеорологічних характеристик та режимів роботи бурової установки

Ключові слова: нафтогазовий комплекс, свердловина, екологічна безпека, атмосферне повітря, моделювання аварійного викиду

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1. Introduction

Virtually all elements of environment are considered as objects of influence during construction and operation of wells. In particular, the following should be distinguished: atmospheric air (AA), surface and ground water, soil and vegetation, biotic complexes, sheet deposits, etc. [1–3]. Despite continuous improvement of oil and gas equipment, facilities and systems of emergency diagnostics and protection, there is a probability of uncontrolled or poorly controlled phenomena and processes. Such facts are classified as an emergency posing a particular danger to biosphere and, above all, to population. Possible causes of occurrence of emergency situations are described in detail in existing literature [4, 5].

Possible emergencies of particular danger include open well gushing. In conditions of both burning and non-burning gas well gushing, toxic substances are coming in AA in large quantities. Then, under action of turbulent diffusion and wind flows, the gas spreads over the drilling site and beyond posing a high risk to environment and health of the drilling personnel and the population of surrounding settlements.

Problems of efficient prevention of emergencies in a case of AA pollution by gas release from gushing wells can be divided into two groups. The problem of the first group consists in a prompt forecasting proceeding from the emergency fact. The problem of the second group consists in early assessment of the pollutant spread in AA under fixed conditions [6–8]. Prediction of actual and potential level of pollutants with a sufficient accuracy is connected with some difficulties. Atmospheric pollution is characterized by spatiotemporal heterogeneity, non-stationarity of release intensity, as well as variation of weather conditions and pattern of release into atmosphere [9, 10].

Spread of a substance (mass, energy) released during emergency, that is, spread of emergency impact can be described by appropriate mathematical models. Current requirements to assessment of this impact on environment cover the necessity of predicting AA pollution in emergency situations but do not contain any specific recommendations. This defines relevance of this study, that is construction of adequate mathematical models of spatial spread of dangerous substances from gushing gas wells (GGW). The models will take into account atmospheric conditions of spread and the release intensity. Such mathematical tool will be useful in assessment and prediction of AA pollution level in the areas of well operation in various critical situations.

2. Literature review and problem statement

The following studies propose technological solutions for effective suppression of gushing gas wells, namely, for example a new method of waterflooding the gas stratum in [11] and use of underground directional blasts [12]. Study [13] presents GIS analysis of the results obtained in measurement of concentration levels of methane, ethane, propane, carbon dioxide and hydrogen sulfide in the territories of gas well operation in a case of emergency non-burning gushing. However, authors of these studies do not touch the issue of elaboration of mathematical modeling tools to define spatiotemporal distribution of concentration of pollutants released in such emergency situations.

Mathematical models of spread of dangerous substances from planar and linear sources are presented in [14]. The proposed models make it possible to estimate level of impact on near-surface atmosphere layer just for technological processes of flushing. Hence, these models do not make it possible to find distribution of toxic substances in emergency GGW.

Study [15] provides an algorithm for calculating parameters of releases and gross releases of harmful substances from flaring facilities where hydrocarbon mixtures are burnt but it does not enable determination of the amount of releases in non-burning gushing.

There are many papers devoted to theoretical studies of atmospheric turbulence and spread of industrial releases. For example, turbulent exchange in an elevated inversion layer is studied in [16], influence of anomalous stratification on initial rise of pollution caused by releases from a technogenic source is considered in [17] and influence of wind speed variation with altitude on distribution of technogenic pollutants in the near-surface atmosphere layers is studied in [18]. However, physical patterns of release, transfer, and dispersion of natural gas in the event of emergency releases are characterized by a considerable complexity and differ significantly from classical releases, such as those from chimneys. First of all, this is objectively related to the non-stationary nature and high speed (up to the sound speed) of gas leakage in the case of emergency situations on wells, significant influence of the underlying surface or generally random spatial orientation of release, etc. Therefore, the results obtained in these studies cannot be used to construct mathematical models of AA pollution by gas release during a non-burning gushing.

Application of integral methods to this problem is reflected in [19–21]. In some cases, one-dimensional jet models proposed by these authors well reproduce distribution of flow parameters along the axis of free jets. However, they cannot collectively account for a series of important factors that are crucial in the event of emergency releases from gas wells and pipelines. Such factors include non-stationarity, non-isothermal release, densities other than air density, existence of a pronounced vertical inhomogeneity of wind speed and turbulence characteristics near surface. This greatly increases occurrence of significant errors in the calculated values of the near-surface concentration. At the same time, in the problems of industrial safety, namely the range of near-surface concentrations is the necessary information.

Study [22] describes application of an engineering procedure to calculation of AA pollution. It was developed in Voyeikov Main Geophysical Observatory (USSR, 1986). However, this procedure has a significant limitation since it defines distribution of technogenic pollutant concentration in just unstable atmosphere state. This makes it inapplicable to other meteorological scenarios. This is unacceptable for preventive forecast of severe emergencies connected with non-burning GGW.

EPA USA procedure was used in [23] to estimate public health risks caused by toxic releases in AA from large industrial enterprises. However, this procedure does not fully take into account specificity of the emergency releases under study. This is explained by the fact that its mathematical apparatus does not take into account turbulence of the emerging jet flow and the processes of heat and mass transfer taking place during pollutant spread in AA. Therefore, this mathematical toolkit cannot be used to support effective decision-making in a case of GGW.

Mathematical models of Gaussian type have found their widespread use in solving the problems of AA protection in areas of chemically hazardous enterprises. For example, a one-dimensional model of defining maximum concentration and the distance at which it arises as a result of release from chemically hazardous enterprise under given meteorological conditions was used in [24], a model of non-stationary release pattern for the study of population health risks in the event of explosion at a potentially hazardous enterprise was used in [25] and the IAEA model of determining power of a release source according to monitoring data was used in [26].

However, the models based on Gaussian distribution function have several essential drawbacks:

– local terrain features and spatiotemporal inconstancy of meteorological parameters are not considered;

– sources working for a limited time are not described; dispersion characteristics obtained for terrestrial but not for input sources are used;

– vertical structure of boundary formation is not taken into account;

– they are only used to define concentration of contaminants with density close to air density;

– they are only used for meteorological situations for which wind speed is not less than 1 m/s.

These shortcomings significantly limit applicability of these models to solve problems of prevention of emergency GGW.

Thus, the performed analysis has shown that there are no mathematical tools for modeling leakage of gas mixtures from a non-burning GGW in various release modes. The mathematical models and procedures developed to describe spread of contaminants in AA from releases of technogenic pollution sources have material drawbacks and limitations. Therefore, in order to solve urgent problems related to prevention of emergency GGW, it is necessary to develop mathematical tools that will adequately describe both movement of the gas mixture in the wellbore and migration of pollutants into AA in various release conditions and meteorological scenarios.

3. The aim and objectives of the study

The study objective is to develop mathematical models of gas leakage from a well and its spread in atmospheric air in a case emergency gushing.

To achieve the objective, the following tasks were set:

– to study physical features of AA pollution during GGW;

– to develop models of a gas mixture leakage from a non-burning gushing well in various release conditions;

– to construct a mathematical model of pollutant spread in AA during gas well gushing;

– to check adequacy of the constructed mathematical model.

4. Materials used in construction of a mathematical model of air pollution in a non-burning gushing gas well

4. 1. Physical features of atmospheric air pollution during gas well gushing

The problem of predicting the level and spread of AA pollution in an open GGW involves two main steps:

– determination (calculation) of volume of gas release, its parameters and composition;

– calculation of pollutant migration in space and time in a near-surface atmosphere layer.

Let us consider physical features of each stage.

Gushing is uncontrolled release of a liquid-gas mixture (gases, oil, water, and other substances) on the surface from a well under action of high natural formational pressure. Pressure in the production column is less than formational pressure. In most cases, gas in a mixture with fluid contained in a formation is the main factor acting in gushing. When operating a well drilled down to a depth with high formation energy, free gas is released from this mixture only in lifting pipes. This process starts at a depth where pressure is below the saturation pressure of the liquid-gas mixture. Under these conditions, hydrostatic pressure and energy of the compressed gas which begins to manifest itself only in the upper part of the well are main driving forces acting in lifting the liquid-gas mixture in the well. As the mixture moves up the wellbore, pressure on gas bubbles decreases while gas volume grows and specific weight of the liquid-gas mixture falls. This causes lift of the fluid level to the well mouth. Thus, gas well gushing is caused by the difference between the pressure in formation and the pressure at the fluid column bottom.

Occurrence of gushing is facilitated by long stoppages and disruption of drilling cyclicity, an inappropriate use of emergency fighting methods [27, 28], opening of formations with highly different lithological and physical characteristics and abnormally high formational pressure and a series of other factors [29].

Scatter of emergency gas release in atmosphere depends on many interrelated factors and release conditions (Fig. 1).

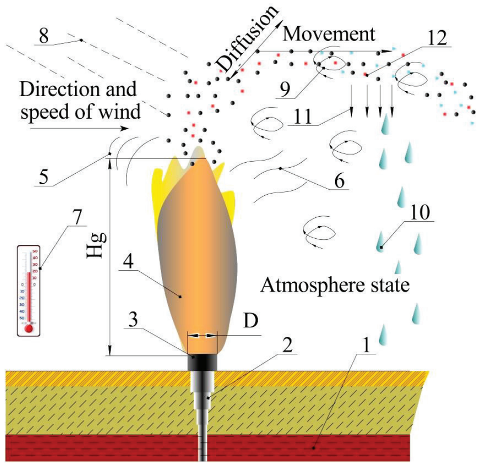

Fig. 1. Features of pollutant scatter in emergency GGW: productive horizon (source) (1); wellbore (2); outlet (3); shape of the jet and its component composition (4); acoustic radiation (5); thermal radiation (when the gush is burning) (6); vertical temperature gradient (7); solar radiation (8); air swirl (9); precipitation (10); dry precipitation (11); formation of new chemical compounds (12); H_g: release height (when the gush is burning); D: the outlet diameter

After pollutants get into AA, pattern of their movement is determined by their own physical properties and properties of atmosphere. Spread and dispersion of emergency release in AA occur as a result of their transfer by wind and turbulent diffusion caused by the presence of disorderly swirls in atmosphere which in a complex way interact with each other and with earth surface.

Effect of wind speed on pollution of the near-surface atmosphere layer is complex. On the one hand, terrestrial pollutant concentrations decrease with an increase in wind speed and on the other hand, strengthening of wind leads to a decrease in the initial pollutant raise height ΔH which contributes to an increase in terrestrial concentration.

In a stationary state of atmosphere, scatter of pollutants slows down and its cloud with considerable concentration can be carried over a long distance. In unstable state of atmosphere, unbalanced elementary volume of air tends to continue its motion. Under these conditions, the pollutant cloud gets quickly eroded [30].

Introduce a concept of effective source height:

$$H_{ef} = H_s + \Delta H, \tag{1}$$

where H_s is the source height (flare stack), m; ΔH is the value of pollutant lift above the source, m.

To calculate the lift height ΔH (m), use the following empirical formula [30, 31]:

$$\Delta H = \frac{1.5 W_0 R_s}{u}\left(2.5 + \frac{3.3 g R_s \Delta T}{T_a u^2}\right), \tag{2}$$

where W_0 is the average rate of pollutant release from the gas well, m/s; R_s is the well mouth radius, m; u is the wind speed at the height of the weather vane (10 m), m/s; ΔT is the gas overheat; T_a is the ambient air temperature in an absolute scale; $g=9.8$ m/s^2 is free fall acceleration.

In the case of short-time release, it lasts several tens of seconds before self-ignition or intended ignition occurs. The wind blows away the gas cloud formed at an altitude as a whole and its expansion is caused by turbulent diffusion both in the wind direction and in the directions perpendicular to it.

In the case of emergency (continuous source of constant intensity), time to the moment of jet ignition will be 10–30 min. The gas ejected from the well is spread in a form of a jet like in the case of stationary flow. In the case of release from the well, the period of sharp change of flow rate is small and shortly after the release start, it stabilizes in a magnitude which is determined by dimensions of the wellbore and formation characteristics.

In addition, spread of pollutants in atmosphere and thus level of their near-surface concentration is affected by fog, precipitations and solar radiation [14, 30].

4. 2. Mathematical model of gas mixture release in non-burning gas well gushing

In the course of modeling, stationary flow of gas from a high-capacity well into atmosphere was considered. The dense jet of cold gas is vertical and has circular cross-section. The gas has the following parameters: $\rho_0>\rho_a$ ($T_0<T_a$) where ρ_0 and ρ_a are density of gas in the cross-section of the well and in air, respectively; T_0 and T_a are temperatures of gas at the outlet and in environment, respectively. Proceed from the conditions that gas is chemically stable, pollutant is passive and does not change density of the air-gas mixture, earth surface is flat, with a uniform roughness and impermeable to the substance.

There is a defining direction of release along which spread of pollutant is mainly convective. Scattering across the stream is diffusive. The assumption on similarity of profiles of transverse distribution of main parameters of the jet (velocity, temperature, and concentration of pollutant) is taken.

4. 2. 1. Mathematical model of stationary release of the gas mixture from the well

To construct this model, assume that a stationary stream of gas mixture moves through the well and the formation. Mass flow rate through any well cross-section is the same:

$$\rho \cdot Q = \text{const}, \tag{3}$$

where Q is the volume flow rate through the cross-section, kg/s; ρ is the average density of the mixture of gases in the cross-section, kg/m^3.

Assume that within the well, the channel along which the gas mixture moves is composed of N rectilinear sections of equal annular cross-section areas. Thus, geometry of the channel is described by a set of the following parameters:

$$l_i,\ d_{out_i},\ d_{in_i},\ \alpha_{z_i},\ i = 1, 2, 3,\ \ldots, N, \tag{4}$$

where l_i is the section length, m; d_{out_i}, d_{in_i} are the outer and inner diameters of the annular section, respectively, m; α_{z_i} is the deviation angle (the angle between direction of the section axis and the vertical), deg.

Within the section, the equation of momentum holds:

$$\frac{\mathrm{d}\left(\rho W^2\right)}{\mathrm{d}l} + \frac{\mathrm{d}P}{\mathrm{d}l} = -\frac{\lambda_i \rho W|W|}{2d_i} + \rho g \cos\alpha_{z_i}, \tag{5}$$

where d_i is the hydraulic diameter calculated by the formula:

$$d_i = d_{out_i} - d_{in_i}, \tag{6}$$

where l is distance from the mouth, m; W is speed of the mixture of gases, m/s (for gushing, speed in expression (5) is negative); P is pressure of the gas mixture, Pa; λ_i is coefficient of hydraulic resistance of the i-th section, n/d (non-dimensional).

Assume that pressure at the section junctions changes continuously (losses caused by the change of cross-section and flow direction are not taken into account).

Equation of state for the mixture of gases is written in the following form:

$$\rho = \rho_{nc} \cdot \frac{T_{nc}}{T} \cdot \frac{1}{Z} \cdot \frac{P}{P_{nc}}, \tag{7}$$

where ρ_{nc}, T_{nc}, P_{nc} are density, temperature, and pressure of the gas mixture under normal conditions.

Density of the gas mixture under normal conditions in volume fractions is found from the formula:

$$\rho_{nc} = 0.01 \sum_{i=1}^{n} c_i \rho_{nc.i}, \tag{8}$$

where c_i is percentage content of the i-th gas in the mixture of n released gases; $\rho_{nc.i}$ is density of the i-th gas in the mixture under normal conditions, kg/m^3.

Average value of the compressibility coefficient Z of the mixture of gases is determined from formula:

$$Z = 1 - 0.0241 \cdot \frac{P\left(P_0\right)}{\Theta}, \tag{9}$$

where

$$P\left(P_0\right) = \frac{P_0}{P_{pc}};$$

$$\Theta = 1 - 1.68T + 0.78T^2 + 0.0107T^3;$$

$$T = \frac{T_0}{T_{pc}};$$

P_0 is pressure at the well mouth, MPa; T_0 is average wellbore temperature of the gas mixture, K.

Pseudocritical pressure P_{pc}, MPa, and temperature T_{pc}, K, of the mixture of released gases are found from formulas:

$$P_{pc} = 0.01\sum_{i=1}^{n} c_i P_{c.i}, \tag{10}$$

$$T_{pc} = 0.01\sum_{i=1}^{n} c_i T_{c.i}, \tag{11}$$

where $P_{c.i}$ and $T_{c.i}$ are critical pressure, MPa, and critical temperature, K, of the i-th gas in the mixture, respectively.

Pressure losses in the formation at stationary filtration are described by the equation:

$$P_{oi}^2 = P_{fp}^2 - aQ_n - bQ_n^2, \tag{12}$$

where P_{oi} is the pressure in the well opposite the operating interval; a and b are the coefficients of linear and quadratic filtration resistance of the well, respectively, kg·cm^2; P_{fp} is formational pressure.

Equation (12) can be regarded as a boundary condition for system (3) to (5). The condition at the mouth is:

$$\begin{aligned} &W_m = C \text{ at } P_m > P_a, \\ &W_m < C \text{ at } P_m = P_a, \end{aligned} \tag{13}$$

where P_m, W_m, C are pressure, gas velocity and sound velocity at the mouth; P_a is atmospheric pressure (if open gushing is considered).

The problem is solved by assuming constancy of temperature of the mixture of gases moving along the well and the coefficient of compressibility:

$$\begin{aligned} &T = \text{const}, \\ &Z = \text{const}. \end{aligned} \tag{14}$$

The problem consists in finding the gushing capacity at specified formation parameters (formational pressure, coefficients of filtration resistance), geometry of the wellbore and parameters of the equation of state (3), (14). Arithmetic mean values of temperature and coefficient of compressibility for formation and mouth conditions will be used as mean values in (14). Equation (5) is solved by the method of interval bisection on halves. The zero value of capacity is taken as the lower limit of the root. The upper limit is defined by calculating the bottom-hole pressure for several successively increasing Q_n values.

Upon determining the gushing capacity, Q_m, at specified internal and external conditions relative to the well, define the mass flow rate of the mixture of gases kg/s: by the following expression:

$$Q'_m = Q_m \rho_{mix}, \tag{15}$$

where ρ_{mix} is the density of the mixture of released gas components at the well mouth, kg/m^3.

The value of ρ_{mix} is defined from equation (7) depending on conditions at the well mouth.

Finding of the mass flow rate of the i-th gas in the mixture, kg/s, is the end result of modeling at this stage:

$$M'_i = Q'_m c_i. \tag{16}$$

Thus, a mathematical model was constructed that describes continuous release of the gas mixture during emergency well gushing and makes it possible to define mass flow rate of each component of the erupted mixture.

4. 2. 2. Mathematical model of a burst release of a mixture of gases from a well

It is assumed that the well is vertical and the channel through which release passes has a constant cross-section. Non-stationary gas flow is described by a system of equations expressing the laws of conservation of mass and momentum:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho W)}{\partial l} = 0, \tag{17}$$

$$\rho \frac{\mathrm{d}W}{\mathrm{d}t} + \frac{\partial P}{\partial l} + g\rho\left(\frac{|W|W}{W_{gid}^2} - 1\right) = 0, \tag{18}$$

where

$$W_{gid} = \sqrt{\frac{2gD_{gid}}{\lambda}}. \tag{19}$$

Write the equation of gas state in the form:

$$P = \rho Z_{mv} R T_{mv}, \tag{20}$$

where

– $\dfrac{\mathrm{d}}{\mathrm{d}t} = \dfrac{\partial}{\partial t} + W\dfrac{\partial}{\partial l}$;

– t is time;

– l is the length along the axis of the wellbore;

– g is acceleration of gravity;

– P, W, ρ are pressure, velocity, and density of gas;

– λ is the coefficient of hydraulic resistance (assumed to be constant);

– D_{gid} is hydraulic diameter of the channel;

– Z_{mv} and T_{mv} are mean values of the compressibility coefficient and the gas temperature.

At the initial moment, the well mouth is closed, and distribution of pressure P_0 in the stationary gas column is described by equation:

$$-\frac{\partial P_0}{\partial l} + g\rho = 0. \tag{21}$$

At the bottom-hole, pressure in the well coincides with the formational pressure:

$$P_0(l_b) = P_{fp}, \tag{22}$$

where l_b is the coordinate of coverage of the interval at which the manifestation of gas kick occurs; P_{fp} is formation pressure at the well locations.

Let instantaneous depressurization of the mouth occur in the moment $t = 0$. Speed in the output cross-section will be equal to the local sound speed and the current capacity is calculated from the formula:

$$Q_h = C_D W_s F_h \rho_h, \tag{23}$$

where Q_h is the gush capacity; W_s is the local speed of sound; F_h is the area of the output section; ρ_h is the density of fluid in the output section; C_D is the coefficient of flow that depends on the shape of the output section.

From this point on, a rarefaction wave will move down the gas column. After reaching the bottom-hole, the wave, partially reflected, will come into the formation where a growing in time pressure sink will form. The method of change of stationary states is used to calculate the release. In accordance with this method, the flow region is divided into two sections. The gas column is at rest in the lower section and a stationary stream is moving in the upper section.

Thus, the following conditions are fulfilled in the near-throat part of the wellbore:

$$\rho F W = Q_h(t) = \text{const}, \tag{24}$$

$$-\frac{\mathrm{d}P}{\mathrm{d}l} - \frac{\mathrm{d}\left(\rho W^2\right)}{\mathrm{d}l} + g\rho\left(1 + \frac{W^2}{W_{gid}^2}\right) = 0. \tag{25}$$

The following condition is fulfilled on the movable boundary:

$$P\left(l_f, t\right) = P_0\left(l_f\right), \tag{26}$$

where l_f is the current position of the front.

Knowing pressure distribution along the wellbore, it is possible to find weight of the gas present in the well at time t. It follows from the above that the weight is completely determined by the front position: $M(t)=M(l_f)$. The following equation of front displacement follows from the condition of material balance applied to the whole wellbore,

$$M' \cdot \frac{\mathrm{d}l_f}{\mathrm{d}t} = Q_h. \tag{27}$$

After the wave has reached the bottom-hole, fluid in the formation gets moving. Assuming the flow is symmetrical about the well axis, denote by R_f the boundary radius (radius of the pressure sink) which separates region of the still fluid from the near-bore region in which flow is stationary and its yield is equal to the instantaneous yield of the gush. To calculate R_f, an equation similar to (27) is used in which M is understood as the weight of gas in the wellbore and circular region of the formation whose radius R_0 is chosen such that $R_f<R_0$ at a given time interval. To find $M(R_f)$, consider the problem of stationary flow in a well – formation system which satisfies the condition in the mouth (23) and the condition in the moving contour:

$$P\left(R_f, t\right) = P_{fp}. \tag{28}$$

In addition, the coupling conditions are fulfilled: a continuous change of pressure and mass flow during the transition from the formation to the well.

For approximate calculation of flow in the formation, the known result of the filtration theory was used: at a constant yield of the well. Displacement of radius R_f in the method of change of stationary states is described by the relation:

$$R_f(t) \approx R_w + 2\sqrt{\eta t}, \tag{29}$$

where η is the piezo conductivity which in the case of a gas formation is found from expression:

$$\eta = \frac{P_{fp} k}{m\mu}, \tag{30}$$

where k is permeability of formation near the well, darcy; m is average formation porosity near the well, n/d (non-dimensional); μ is gas viscosity in formation conditions, cP.

4. 3. Mathematical model of pollutant spread in atmospheric air in a case of gas well gushing

To construct mathematical model of pollutant spread in AA in a case of release from the gas well, the following assertions were made:

1) medium is continuous and incompressible;

2) atmospheric turbulence is isotropic and inhomogeneous;

3) only turbulent diffusion of a gradient type occurs during pollutant transfer and molecular diffusion is neglected;

4) the pollutant released into atmosphere are considered to be «passive pollutants», that is the ones that do not change aerodynamics of the air flow into which they enter;

5) air movement is stationary;

6) a mixture of gases having quite small precipitation rate enters atmosphere, that is it is neglected.

Taking into account the aforementioned assertions and assumptions, a function $q(t, x, y, z)$ was found which defines pollutant conncentration in space and time in conditions of a burst release of a pollutant weight M from a point source located in $(0, 0, H_{ef})$ at a point of time $t=0$. For this purpose, the following empirical equation of turbulent diffusion with corresponding initial and boundary conditions was solved [30]:

$$\frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y} + w\frac{\partial q}{\partial z} + \lambda q =$$

$$= K_x \frac{\partial^2 q}{\partial x^2} + K_y \frac{\partial^2 q}{\partial y^2} + K_z \frac{\partial^2 q}{\partial z^2} + M\delta(t)\delta(x)\delta(y)\delta\left(z - H_{ef}\right), \tag{31}$$

initial conditions:

$$uq = M\delta(x)\delta(y)\delta\left(z - H_{ef}\right) \text{ at } t=0;$$

boundary conditions:

$$q \to 0 \text{ at } x^2+y^2+z^2 \to \infty$$

and

$$K_z \frac{\partial q}{\partial z} + wq + \beta q = 0 \text{ at } z=z_0;$$

- u, v, w are the coordinates of the wind speed vector, m/s;
- K_x, K_y, K_z are the turbulent diffusion coefficients, m^2/s;
- λ is the parameter that takes into account the change in pollutant concentration caused by such processes as chemical transformation, precipitate washing, sediment absorption by underlying surface, etc., s^{-1};
- z_0 is the parameter that determines roughness of the underlying surface, m;
- β is the parameter characterizing the pollutant interaction with the underlying surface (reflection or absorption), m/s;
- t is the pollutant spread time, s;
- δ is the Dirac delta function.

The idea of solving equation (31) consisted in reduction of the number of calculations by splitting a three-dimensional problem into a sequence of one-dimensional problems in such a way that both the structure of solution and its basic properties are preserved [32]. In this case, due to the homogeneous boundary conditions, fundamental solution of the spatial equation was represented as a combination (coalescence) of fundamental solutions of corresponding problems:

$$\frac{\partial f(t,x_i)}{\partial t}=K_{x_i}(t)\frac{\partial^2 f(t,x_i)}{\partial x_i^2}-$$
$$-u_i(t)\frac{\partial f(t,x_i)}{\partial x_i}+\delta(t-t_0)\delta(x_i-x_0),\ f(t_0,x_i)=0 \qquad (32)$$

in each spatial coordinate $i=1, 2, 3$.

The equation addend $\lambda(t)\cdot q(t)$ characterizing loss of pollutant during its diffusion was excluded from the solution by substituting the function:

$$q(t,x,y,z)=e^{-\int_{t_0}^{t}\lambda(t)\mathrm{d}t}\cdot f(t,x). \qquad (33)$$

To solve equations (32), the coordinate system was modified:

$$\xi=\int_{t_0}^{t}K_x(t)\mathrm{d}t=\eta(t),\quad \vartheta=x-\int_{t_0}^{t}u(t)\mathrm{d}t, \qquad (34)$$

$$\frac{\partial f}{\partial t}=\frac{\partial f}{\partial \xi}\cdot K_x(t)-\frac{\partial f}{\partial \vartheta}u(t);\ \frac{\partial f}{\partial x}=\frac{\partial f}{\partial \vartheta};\ \frac{\partial^2 f}{\partial x^2}=\frac{\partial^2 f}{\partial \vartheta^2}, \qquad (35)$$

and, following the substitution with taking into account the function change, the following nonlinear differential equation with partial derivatives was obtained:

$$\frac{\partial f'}{\partial \xi}=\frac{\partial^2 f'}{\partial \vartheta^2}+\frac{e^{\int_{t_0}^{\eta^{-1}(\xi)}\lambda(t)\mathrm{d}t}}{K_x\left(\eta^{-1}(\xi)\right)}\times$$
$$\times\,\delta\left(\eta^{-1}(\xi)\right)\delta\left(\vartheta-x_0+\int_{t_0}^{\eta^{-1}(\xi)}u(t)\mathrm{d}t\right). \qquad (36)$$

The Fourier transform method [32] for variable ϑ was used to solve it and inverse change of the function and coordinates was performed. In order to finally obtain solution of equation (31), the obtained solutions of equations (32) were glued [32].

To find the function of concentration $q(t, x, y, z)$ under conditions of short-time contaminant release of duration t_1, a convolution procedure [32] was applied to solve equation (31) for t. In order to find a function describing spatial distribution of concentration at a continuous release of intensity M from a point source, t_1 was replaced by t in the model for the short-lived source. After that, boundary from the right side of the obtained equality was taken with directing t to infinity.

When solving equation (31), the Ox axis was positioned along the wind direction which is not always convenient. When solving practical problems, the coordinate system is usually positioned so that the abscissa axis is oriented in the east direction, that is the basic $Oxyz$ coordinate system is fixed. Under these conditions, wind direction may differ from direction of the Ox axis and form a certain angle α formed with it. To use the models under these conditions, it is necessary to perform modeling in the coordinate system Ox_1y_1z where the axis Ox_1 is directed along the wind direction and then transfer the obtained results to the $Oxyz$ coordinate system using the transition formulas:

$$\begin{cases} x_1=x\cos\alpha+y\sin\alpha, \\ y_1=-x\sin\alpha+y\cos\alpha. \end{cases} \qquad (37)$$

After all mathematical transformations, analytical dependences forming the mathematical model of atmospheric pollution under non-stationary and stationary conditions of release from the GGW have the form:

$$q(t,x,y,z)=\frac{Me^{-\frac{\left(x\cos\alpha+y\sin\alpha-u_{H_{ef}}t\right)^2+(-x\sin\alpha+y\cos\alpha)^2}{4Kt}}}{8\pi\sqrt{\pi K^2K_zt^3}}\times$$
$$\times\left(e^{-\frac{\left(z-H_{ef}\right)^2}{4K_zt}}+e^{-\frac{\left(z+H_{ef}-2z_0\right)^2}{4K_zt}}\right)\cdot e^{-\frac{\lambda(x\cos\alpha+y\sin\alpha)}{u_{H_{ef}}}}; \qquad (38)$$

for an instant release source:

$$q(t,x,y,z)=$$
$$=\frac{Me^{-\frac{\lambda(x\cos\alpha+y\sin\alpha)}{u_{H_{ef}}}}}{8\pi\sqrt{\pi K^2K_z}}\cdot\int_0^{t_1}\frac{e^{-\frac{\left(x\cos\alpha+y\sin\alpha-u_{H_{ef}}(t-\tau)\right)^2+(-x\sin\alpha+y\cos\alpha)^2}{4K(t-\tau)}}}{\sqrt{(t-\tau)^3}}\times$$
$$\times\left(e^{-\frac{\left(z-H_{ef}\right)^2}{4K_z(t-\tau)}}+e^{-\frac{\left(z+H_{ef}-2z_0\right)^2}{4K_z(t-\tau)}}\right)\mathrm{d}\tau; \qquad (39)$$

for a short-time release source of duration t_1:

$$q(x,y,z)=\frac{e^{\frac{u_{H_{ef}}(x\cos\alpha+y\sin\alpha)}{2K}}}{4\pi K\sqrt{K_z}}\times$$
$$\times\left(\frac{e^{-\frac{1}{2}\sqrt{\frac{x^2+y^2}{K}+\frac{\left(z-H_{ef}\right)^2}{K_z}}\cdot\sqrt{\frac{u_{H_{ef}}^2}{K}}}}{\sqrt{\frac{x^2+y^2}{K}+\frac{\left(z-H_{ef}\right)^2}{K_z}}}+\right.$$
$$\left.+\frac{e^{-\frac{1}{2}\sqrt{\frac{x^2+y^2}{K}+\frac{\left(z+H_{ef}-2z_0\right)^2}{K_z}}\cdot\sqrt{\frac{u_{H_{ef}}^2}{K}}}}{\sqrt{\frac{x^2+y^2}{K}+\frac{\left(z+H_{ef}-2z_0\right)^2}{K_z}}}\right)\cdot e^{-\frac{\lambda(x\cos\alpha+y\sin\alpha)}{u_{H_{ef}}}}. \qquad (40)$$

for continuous release source where $u_{H_{ef}}$ is the wind speed at an effective height of the release source, m/s. When constructing the model, it was assumed that $K_x=K_y=K$.

In analytical dependence (40), M means the release intensity in g/s. The wind speed at the effective height of the release source is defined from formula [30]:

$$u_{H_{ef}}=u(10)\cdot\frac{H_{ef}^{\varepsilon}-z_0^{\varepsilon}}{10^{\varepsilon}-z_0^{\varepsilon}}, \qquad (41)$$

where $u(10)$ is the wind speed at an altitude of 10 m, m/s; ε is dimensionless parameter depending on the category of atmosphere stability.

Adequacy of the mathematical models constructed was verified by comparing the modeling results with the data of field measurements of concentration of toxic substances in composition of the emergency release during gushing in one of the wells in the gas-condensate field of Poltava region. This emergency occurred in 2015 on a mothballed gas well because of depressurization during repair work. A gush of gas and condensate mixture lasted for several days. Pollutant concentration was measured in the well location.

The modeling input data were as follows:

– *well parameters*: depth: 5.471 m; first section: length: 1.526 m; outer and inner diameters of the annular section: 0.168 m and 0.14 m, respectively; second section length: 3.550 m; outer and inner diameters of the annular section: 0.245 m and 0.168 m, respectively; third section length: 395 m; outer and inner diameter of the annular section: 0.351 m and 0.245 m, respectively; deviation angle of all sections: 0°; flare stack height: 5 m; formational pressure: 37.3 MPa; gas pressure at the pipe mouth: 16.1 MPa; coefficient of hydraulic resistance: 0.08; average coefficient of compressibility: 1; linear filtration resistance factor of the well: 2 kg·cm^2; coefficient of quadratic filtration resistance of the well: 0.001 kg·cm^2; permeability of formation in the vicinity of the well: 0.1 darcy; average porosity of formation in the vicinity of the well: 0.12;

– *content and parameters of the gas mixture being released*: as per Table 1;

– *meteorological parameters*: air temperature: 289 K; atmospheric pressure: 0.1 MPa; wind speed: 3 m/s; wind direction: southwest; atmosphere state: neutral; coefficients of turbulent diffusion: 75 m^2/s (horizontal): 15 m^2/s (vertical); precipitations: absent; humidity: 75 %;

– *parameters of the adjacent territory*: flat earth surface; underlying surface unevenness: 0.07 m.

In order to check adequacy of the constructed mathematical models, distribution of concentration of all substances (Table 1) was simulated in MATLAB 7. As an example, Fig. 2 shows results of simulation of methane distribution in the near-surface atmosphere layer at a height of 1.5 m from the earth surface.

In addition, Fig. 2 shows the places where the gas pollutant concentrations were measured by emergency service.

As an example, comparison of modeling and measurement results obtained for methane and hydrogen sulfide is given in Table 2.

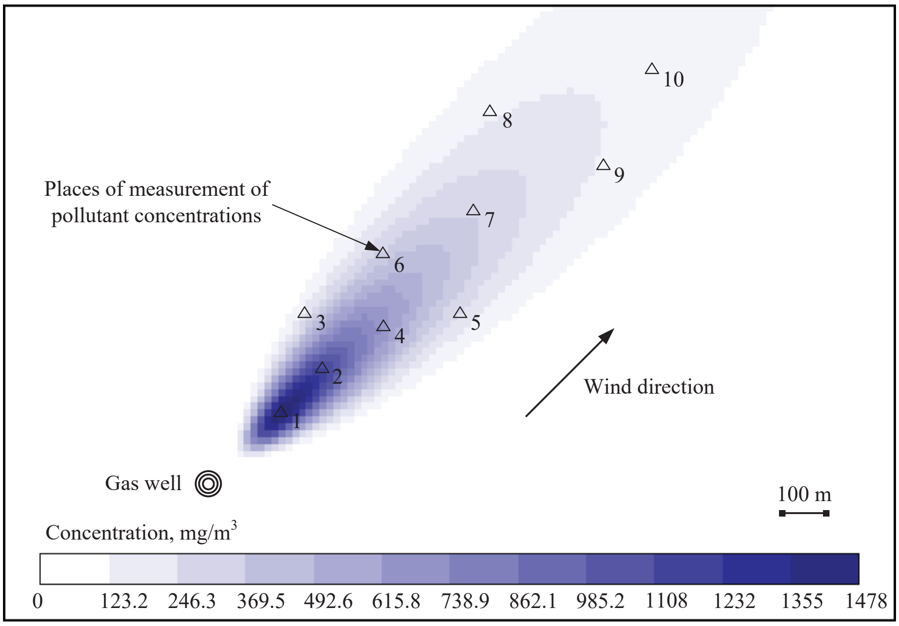

Fig. 2. Visualization of the results of simulation of methane distribution in AA as a result of emergency eruption at the gas well under study

Table 2

Comparison of modeling and field measurement results

No.	Methane			Hydrogen sulfide		
	C_{fm}, mg/m^3	C_{mod}, mg/m^3	Δ, %	C_{fm}, mg/m^3	C_{mod}, mg/m^3	Δ, %
1	1.520	1.478	2.8	0.0324	0.031	4.5
2	990	1.066	7.1	0.0211	0.0198	6.6
3	150	137	9.5	0.0032	0.0031	3.2
4	700	626	11.8	0.0149	0.0175	14.9
5	250	231	8.2	0.0053	0.0054	1.9
6	330	329	0.3	0.007	0.0064	9.4
7	270	281	3.9	0.0057	0.0065	12.3
8	112	130	14.5	0.0023	0.0024	4.2
9	130	136	4.4	0.0027	0.003	10.0
10	110	119	7.6	0.0023	0.0021	9.5

Note: C_{fm}, C_{mod} are the substance concentrations according to field measurements and modeling, respectively; Δ is relative error of modeling

Table 1

Data of the gas mixture released during gushing

Components	Content, vol. %	Molecular weight, kg/mol	Density, kg/m^3	Pseudocritical pressure, MPa	Pseudocritical temperature, K
Methane	52.885	16.041	0.717	4.640	190.66
Ethan	2.541	30.07	1.356	4.884	305.46
Propane	1.068	44.097	2.019	4.255	369.90
Butane	0.687	58.124	2.703	3.799	425.20
Pentane+the above	3.611	72.151	3.457	3.373	469.50
Nitrogen	0.042	28.016	1.250	3.394	126.20
Carbon dioxide	11.896	44.011	1.977	7.386	304.26
Hydrogen sulfide	27.27	34.082	1.541	9.007	373.60

Similar comparisons were obtained for other components of release.

The first thing to note is that under such conditions of gushing the well under study in near-surface atmosphere layer, maximum concentration levels of all substances exceeded corresponding maximum permissible concentrations by 4–5 times.

This indicates a significant health risk to the well staff and the population of the surrounding area when inhaling air at such emergencies.

Second, proceeding from the comparison results, it was established that the maximum relative error of modeling did not exceed 15 %. This is absolutely acceptable for this class of problems. The results confirmed high adequacy of the constructed mathematical models of gas release and distribution in AA as a result of non-burning GGW.

5. Discussion of results obtained in the construction of mathematical models of atmospheric air pollution by a non-burning gas well gushing

The mathematical tools that were developed are effective in solving problems of emergency prevention in case of non-burning gas well gushing. Mathematical model of stationary release of a gas mixture from a well (p. 4. 2. 1) has allowed us to find release power for each component of the gas mixture at stationary conditions of emergency gushing and the model of burst release of the gas mixture (p. 4. 2. 2) gives weight of release at a non-stationary release of toxic gases from the well mouth. These models are presented as a set of corresponding algebraic and differential equations describing gas flow in the well. The models take into account all major physical factors influencing gas flow in the wellbore. To use them, it is necessary to have data on gas-dynamic and geometric characteristics of formation and wells. This information should be entered to the detail design and passport of the well.

Mathematical models of pollutant spread in AA have been obtained in analytical form which greatly simplifies their implementation and use. These models allow the designers to determine distribution of pollutants in space and time in the adjacent well territory under conditions of burst gushing (model (38)), short-term gushing (model (39)) and continuous gushing (model (40)). Weight (non-stationary gushing mode) or intensity (stationary mode) of release, source and conditions of release, pollutant parameters and meteorological conditions are input data for these models.

The mathematical models constructed have significant advantages over the existing ones, that is the models and methodological recommendations based on Gaussian distribution. For example, they take into account peculiarity of the underlying surface and interaction of pollutants with environment (precipitation washing-out, chemical transformation, absorption of the underlying surface) and vertical structure of the boundary formation. They can also be used to define concentration of any gaseous pollutants of various densities. Besides, they make it possible to determine pollutant concentration under release and meteorological conditions. This enables solution of a broader range of problems related to monitoring of AA status in the territories where gas wells are operated.

To obtain results of application of these models, it is necessary to use specialized software that allows one to solve ordinary differential equations and equations with partial derivatives in corresponding initial and boundary conditions.

At the current stage, the developed mathematical models were implemented in the MATLAB 7 software environment which allows us to quickly obtain modeling results from the input data. Verification of adequacy of the developed models according to the real emergency gushing of one of the gas wells in Poltava region has shown their high accuracy: modeling error did not exceed 15 % for all components of the gas mixture.

It is worth noting that the models developed by the authors do not take into account terrain features and therefore high accuracy of modeling will only be ensured in the conditions of flat terrain up to distances of 30 km. As the terrain becomes more complex and distance from the source of release increases, modeling accuracy will decrease. Also, it is obvious that to improve accuracy of modeling, it is necessary to ensure high accuracy of the input data.

In some cases, conditions of emergency gushing do not allow measurements to be made to the required extent. Thus, in the case of gushing, intensity of flow of the released fluid can vary in time. Qualitative composition of releases is unpredictable and unstable: liquid, liquid-gas mixture, or gas. Therefore, it is necessary to use in practice some non-standard and fairly approximate methods as well as involve data on the features of the emergency well drilling history, circumstances of occurrence of gas kick and its transition into an uncontrolled gush. Given the complexity of field studies in real conditions, it is appropriate to develop a physical model using ejection systems [31] which will make it possible to experimentally study possible scenarios of formation of a fluid flow from a well and bring them as close as possible to real conditions.

The constructed models can be used to solve problem of prompt forecast after emergency occurrences and early calculation of pollutant spread in atmosphere under fixed conditions. This approach can be useful both in the complex design of new wells and planning safety measures for existing wells, in particular for estimating the maximum possible concentrations of planned releases. As an example, there would be a wellbore where it is necessary to define whether the maximum permissible concentrations of toxic components will be exceeded under given atmospheric scattering conditions at the border of the sanitary-protective zone round the drilling rig and in neighboring settlements [1, 2, 8].

Further studies will be directed to development of a specialized modeling software complex which will be an effective tool for supporting decision making in the management of environmental safety of AA in the territories of gas wells. It will include various functional modules. Their use will enable computerized mapping of hypothetical and actual pollution during emergency GGW, analyze the data and assess health risks of staff and population of the surrounding areas, etc. [33].

7. Conclusions

1. The study of physical features of atmospheric air pollution during non-burning gas well gushing has allowed us to establish the following. The main parameters that define weight (intensity) of release of the gas mixture components are as follows:

– pressure and temperature in the well;

– hydraulic and filtration resistance of the well;

– atmospheric pressure;

– ambient air temperature;

– well geometry;

– formation characteristics in the well location (permeability, porosity and thickness, gas pressure and viscosity in formation conditions);

– percentage of components in the gas mixture.

The main parameters that define distribution of pollutant concentration in space and time are as follows:

– release parameters (duration, power, temperature, rate of flow of pollutants from the well, height, and radius of the source mouth);

– meteorological characteristics (wind speed and direction, temperature gradient with altitude, turbulent diffusion coefficients, air temperature);

– parameters of pollutant and environment interaction (precipitation, underlying surface, other pollutants);

– roughness of the underlying surface;

– spread time and rate of pollutant deposition (for heavy pollutants).

2. Mathematical models of stationary and burst release of a mixture of gases from a well as differential equations with corresponding initial and boundary conditions were constructed. These models take into account all main factors affecting intensity of the gas mixture flow in the case of emergency gas well gushing.

3. A mathematical model of pollutant dispersion in atmospheric air was constructed. Unlike the existing ones, it takes into account all main factors influencing this process. This model makes it possible to establish distribution of concentration in space and time under stationary and non-stationary release conditions and at various meteorological scenarios. This will effectively solve the problems of monitoring atmospheric air in the areas of gas wells and preventive forecasting of emergency situations related to emergency gushing.

4. Adequacy of the developed mathematical models was checked by comparing the modeling results with the data of field measurement of concentration of toxic gaseous substances in atmospheric air during gushing of one of the wells of the gas-condensate field in Poltava region. It was found that the modeling error did not exceed 15 % for all components of the gas mixture which is absolutely acceptable for this class of problems. This confirms high adequacy of the constructed models and the prospects of their application to solve actual problems of air protection in the territories of gas wells.

References

1. Werner, A. K., Vink, S., Watt, K., Jagals, P. (2015). Environmental health impacts of unconventional natural gas development: A review of the current strength of evidence. Science of The Total Environment, 505, 1127–1141. doi: https://doi.org/10.1016/j.scitotenv.2014.10.084
2. McKenzie, L. M., Witter, R. Z., Newman, L. S., Adgate, J. L. (2012). Human health risk assessment of air emissions from development of unconventional natural gas resources. Science of The Total Environment, 424, 79–87. doi: https://doi.org/10.1016/j.scitotenv.2012.02.018
3. Kovach, V., Lysychenko, G. (2017). Toxic Soil Contamination and Its Mitigation in Ukraine. Soil Science Working for a Living, 191–201. doi: https://doi.org/10.1007/978-3-319-45417-7_18
4. Sule, I. O., Khan, F., Butt, S. (2018). Experimental investigation of gas kick effects on dynamic drilling parameters. Journal of Petroleum Exploration and Production Technology, 9 (1), 605–616. doi: https://doi.org/10.1007/s13202-018-0510-z
5. Chadwell, L. J., Blundon, C., Anderson, C., Cacho, H. M. (2000) Incidents Associated with Oil and Gas Operations. Herndon, VA. Available at: https://www.bsee.gov/sites/bsee.gov/files/incident-summaries/incident-histories/finalocs98-pdf.pdf
6. Macey, G. P., Breech, R., Chernaik, M., Cox, C., Larson, D., Thomas, D., Carpenter, D. O. (2014). Air concentrations of volatile compounds near oil and gas production: a community-based exploratory study. Environmental Health, 13 (1). doi: https://doi.org/10.1186/1476-069x-13-82
7. Chudnovskiy, D. M., Dolgushin, V. A., Leontyev, D. S., Krushevskiy, S. V. (2015). Fountain prevention is better than elimination. Problemy sbora, podgotovki i transporta nefti i nefteproduktov, 2, 202–207.
8. Lysychenko, G., Weber, R., Kovach, V., Gertsiuk, M., Watson, A., Krasnova, I. (2015). Threats to water resources from hexachlorobenzene waste at Kalush City (Ukraine) – a review of the risks and the remediation options. Environmental Science and Pollution Research, 22 (19), 14391–14404. doi: https://doi.org/10.1007/s11356-015-5184-1
9. Popov, O., Iatsyshyn, A., Kovach, V., Artemchuk, V., Taraduda, D., Sobyna, V. et. al. (2019). Analysis of Possible Causes of NPP Emergencies to Minimize Risk of Their Occurrence. Nuclear and Radiation Safety, 1 (81), 75–80. doi: https://doi.org/10.32918/nrs.2019.1(81).13
10. Edwards, P. M., Young, C. J., Aikin, K., deGouw, J., Dub , W. P., Geiger, F. et. al. (2013). Ozone photochemistry in an oil and natural gas extraction region during winter: simulations of a snow-free season in the Uintah Basin, Utah. Atmospheric Chemistry and Physics, 13 (17), 8955–8971. doi: https://doi.org/10.5194/acp-13-8955-2013
11. Litovitz, A., Curtright, A., Abramzon, S., Burger, N., Samaras, C. (2013). Estimation of regional air-quality damages from Marcellus Shale natural gas extraction in Pennsylvania. Environmental Research Letters, 8 (1), 014017. doi: https://doi.org/10.1088/1748-9326/8/1/014017
12. Soeder, D. J., Sharma, S., Pekney, N., Hopkinson, L., Dilmore, R., Kutchko, B. et. al. (2014). An approach for assessing engineering risk from shale gas wells in the United States. International Journal of Coal Geology, 126, 4–19. doi: https://doi.org/10.1016/j.coal.2014.01.004
13. Garcia-Aristizabal, A., Capuano, P., Russo, R., Gasparini, P. (2017). Multi-hazard risk pathway scenarios associated with unconventional gas development: Identification and challenges for their assessment. Energy Procedia, 125, 116–125. doi: https://doi.org/10.1016/j.egypro.2017.08.087
14. Shkitsa, L. E., Yatsyshyn, T. M., Popov, A. A., Artemchuk, V. A. (2013). The development of mathematical tools for ecological safe of atmosfere on the drilling well area. Neftyanoe hazyaystvo, 11, 136–140.
15. Metodika rascheta parametrov vybrosov i valovyh vybrosov vrednyh veshchestv ot fakel'nyh ustanovok szhiganiya uglevodorodnyh smesey (1996). Moscow: VNIIgaz, 45.

16. Cabaneros, S. M., Calautit, J. K., Hughes, B. R. (2019). A review of artificial neural network models for ambient air pollution prediction. Environmental Modelling & Software, 119, 285–304. doi: https://doi.org/10.1016/j.envsoft.2019.06.014
17. Danaev, N. T., Temirbekov, A. N., Malgazhdarov, E. A. (2013). Modeling of Pollutants in the Atmosphere Based on Photochemical Reactions. Eurasian Chemico-Technological Journal, 16 (1), 61–71. doi: https://doi.org/10.18321/ectj170
18. Nikezic, D., Loncar, B., Grsic, Z., Dimovic, S. (2014). Mathematical modeling of environmental impacts of a reactor through the air. Nuclear Technology and Radiation Protection, 29 (4), 268–273. doi: https://doi.org/10.2298/ntrp1404268n
19. Kim, H., Lee, J.-T. (2019). On inferences about lag effects using lag models in air pollution time-series studies. Environmental Research, 171, 134–144. doi: https://doi.org/10.1016/j.envres.2018.12.032
20. Alimissis, A., Philippopoulos, K., Tzanis, C. G., Deligiorgi, D. (2018). Spatial estimation of urban air pollution with the use of artificial neural network models. Atmospheric Environment, 191, 205–213. doi: https://doi.org/10.1016/j.atmosenv.2018.07.058
21. Lu, J., Dai, H. C. (2018). Numerical modeling of pollution transport in flexible vegetation. Applied Mathematical Modelling, 64, 93–105. doi: https://doi.org/10.1016/j.apm.2018.06.039
22. Clauset, A., Post, K. (2019). Modeling air pollution regulation. Science, 364 (6438), 347. doi: https://doi.org/10.1126/science.364.6438.347-a
23. Abdallah, C., Afif, C., El Masri, N., Öztürk, F., Keleş, M., Sartelet, K. (2018). A first annual assessment of air quality modeling over Lebanon using WRF/Polyphemus. Atmospheric Pollution Research, 9 (4), 643–654. doi: https://doi.org/10.1016/j.apr.2018.01.003
24. Steinberga, I., Sustere, L., Bikse, J., Jr, J. B., Kleperis, J. (2019). Traffic induced air pollution modeling: scenario analysis for air quality management in street canyon. Procedia Computer Science, 149, 384–389. doi: https://doi.org/10.1016/j.procs.2019.01.152
25. Lancia, G., Rinaldi, F., Serafini, P. (2018). A Facility Location Model for Air Pollution Detection. Mathematical Problems in Engineering, 2018, 1–8. doi: https://doi.org/10.1155/2018/1683249
26. Song, C., Huang, G., Zhang, B., Yin, B., Lu, H. (2019). Modeling Air Pollution Transmission Behavior as Complex Network and Mining Key Monitoring Station. IEEE Access, 7, 121245–121254. doi: https://doi.org/10.1109/access.2019.2936613
27. Drozdova, T. I., Ryabtsev, M. A. (2018). Analysis of causal relationships of gas fountain inflammation in the gas-condensate deposit. XXI Century. Technosphere Safety, 3 (4), 112–120. doi: https://doi.org/10.21285/1814-3520-2018-4-112-120
28. Yatsyshyn, T. M. (2017). Analiz vplyvu avariynykh sytuatsiy na navkolyshnie seredovyshche pry burinni naftohazovykh sverdlovyn. Modeliuvannia ta informatsiyni tekhnolohiyi, 78, 81–88.
29. Yatsyshyn, T. M. (2018). The choice of criteria for environmental risks management system during oil and gas wells construction. Prospecting and Development of Oil and Gas Fields, 2 (67), 31–40. doi: https://doi.org/10.31471/1993-9973-2018-2(67)-31-40
30. Popov, O., Yatsyshyn, A. (2017). Mathematical Tools to Assess Soil Contamination by Deposition of Technogenic Emissions. Soil Science Working for a Living, 127–137. doi: https://doi.org/10.1007/978-3-319-45417-7_11
31. Kryzhanivskyi, Y. I., Panevnyk, D. O. (2019). The study on the flows kinematics in the jet pump's mixing chamber. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 1, 62–68. doi: https://doi.org/10.29202/nvngu/2019-1/7
32. Kaptsov, O. V. (2009). Metody integrirovaniya uravneniy s chastnymi proizvodnymi. Moscow: Fizmatlit, 184.
33. Popov, O., Iatsyshyn, A., Kovach, V., Artemchuk, V., Taraduda, D., Sobyna, V. et. al. (2018). Conceptual Approaches for Development of Informational and Analytical Expert System for Assessing the NPP impact on the Environment. Nuclear and Radiation Safety, 3 (79), 56–65. doi: https://doi.org/10.32918/nrs.2018.3(79).09