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CONSTRUCTION OF AN ALGORITHM FOR BUILDING REGIONS OF QUESTIONABLE DECISIONS FOR DEVICES CONTAINING GASES IN A LINEAR MULTIDIMENSIONAL SPACE OF HAZARDOUS FACTORS

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У лінійному багатовимірному безперервному просторі небезпечних факторів розглянута проблема небезпеки виробничих пристроїв з горючими газами. Небезпечні фактори поділяються на фактори, пов'язані з виробничими пристроями та фізико-хімічними властивостями газів, що знаходяться в цих пристроях. Реально існуючі горючі гази характеризуються чисельними дискретними властивостями, такими як молекулярна маса, питома теплота згоряння і т. д. Абстрактний модельний простір газів представлений в просторі небезпечних факторів точками, координати яких є фізико-хімічними властивостями газів. Внаслідок безперервності простору небезпечних факторів реальні гази будуть представлені окремими точками в цьому просторі або областями в яких безперервно змінюються деякі властивості, наприклад температура, щільність, обсяг і т. д. Крім цього, буде існувати велика кількість точок, в яких властивості газів є несумісними, тобто такими, які неможливі для реальних газів. Це дозволило розглянути проблему небезпеки горючих газів з деяких загальних позицій. Так, використовуючи методологію p-функцій, вдалося розділити простір небезпечних факторів на небезпечну і безпечні частини. Також вдалося виявити прикордонні області, в яких завдання визначення небезпеки пристрою є некоректною. Це означає, що деяка варіація небезпечних факторів в межах точності, з якої вони відомі, призводить до різних, взаємовиключних висновків про небезпеку. Такі області названі областями сумнівних рішень. З'ясовано, що області сумнівних рішень можуть мати складну форму і їх розмір залежить від точності, з якою відомі кількісні значення небезпечних факторів. Розроблено алгоритм побудови областей сумнівних рішень і визначення, чи належить пристрій з газом області сумнівних рішень. Показано, що визначення, чи знаходиться пристрій в області сумнівних рішень, являє собою чисельну задачу, що однозначно вирішується

Ключові слова: потенційно небезпечні об'єкти, імітаційне моделювання, об'єкт підвищеної небезпеки, категорія пожежовибухобезпеки, пожежна небезпека, p-функція

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1. Introduction

It is almost impossible to find an industry that does not use any of the combustible gases. The most common are ammonia, arsine, acetylene, butane, hydrogen, carbon monoxide, methane, propane, propylene, silane, some refrigeration agents, cyclopropane (anesthesia), ethane, ethylene. The variety of hazardous gases and their properties makes it difficult to choose factors of danger, to prevent fires, to early detect the signs of fire, to build sensors to identify fire hazards. Many gases are of complex origin and are obtained accordingly. They are produced in different places, under different conditions, at different times, through different obtaining, storing, and processing techniques. As a result, many properties of formally identical gases (the same according to specifications) might somewhat vary [1, 2]. Often such properties as gas density, specific heat of combustion, the lower and upper limits of flame propagation, undergo such changes. These changes result in a mismatch between the estimated source data and actual ones. There are other objective and subjective reasons for errors in the original data due to inaccuracies in the numerical determination of equipment characteristics, operating conditions, or properties of substances [3, 4]. Uncertainties in the properties of gases and operating conditions of equipment lead to the uncertainty of results from defining the danger of industrial facilities that utilize these gases and equipment. The magnitude of uncertainty depends on the robustness of the mathematical algorithm used in these cases. In this regard, the need to improve the reliability of ways to identify danger emanating from industries raises the task of improving the methods for determining the robustness of algorithms that define the dangers emanating from industrial devices.

2. Literature review and problem statement

Hazard assessment of facilities is an integral part of the industrial safety system. Mistakes in this area can cause harm to the environment, increase complexity. The initial errors that induce such hazards may be the magnitudes that serve as the raw data to algorithms for determining industrial hazards [5]. The importance of assessing industrial hazards is also due to its significance for the prevention and elimination of emergencies [6]. Thus, it is a relevant task to define the degree of danger emanating from industrial devices in general and stand-alone devices that contain gases (outdoor installations) in particular. Determining the suitability of hazard detection methods is particularly important. No similar studies into existing methods for determining danger emanating from industrial facilities have been found. Related studies have been found [7]. In an implicit form, information about errors is included in paper [8]. Under conditions of uncertainty in the source data, the assessment of hazard from a device, object, industry is also uncertain. The challenge is to determine the reliability of such assessments. It is necessary to determine the conditions under which one can be sure in the result from a hazard assessment and the conditions under which the algorithm produces uncertain results, that is results that may change when the initial data change within their accuracy. Since determining dangers from devices and industries in general, and gas-containing devices in particular, is a very important task, the relevance of defining the reliability of methods used here should not be questioned. The research cycle was prompted by emerging issues about the necessary accuracy of initial data for determining hazards at premises and in the outdoor gas installations. Data on this issue were not available in both the regulatory base and the available reported research results. At first, the robustness of the mathematical algorithm underlying relevant regulations was investigated [9]. The study of deficiencies in the quality of a regulatory document related to inaccuracies in the original data was reported in paper [10]. Another study contained an inaccuracy in the numerical value of the participation rate of combustible gases and fumes in burning [11].

Paper [7] examines the impact of the inaccuracy in original data on the resulting hazard of objects. The sensitivity of a hazard calculation algorithm was investigated by statistical methods. The calculations involve simulation modeling using a computer. At specific values for most variables and a small number of randomly altered variables, statistical characteristics of the calculation results are determined. Studies have been carried out in this field, in particular [9], in relation to other algorithms for determining hazards of industrial devices. The approach, described in it, is designed to determine the error of determining the danger of objects in specific cases. Work [12] proposes an algorithm to assess the overall danger by creating indices to rank various sectors in the chemical industry based on the hazards they pose, the risk of fire, explosion, and toxicity. This approach was devised to compare alternative processes to choose the one that is inherently the safest. Paper [13] is interesting because using fuzzy logic makes it possible to convert fuzzy expert opinions into assessments of the probabilities of dangerous events. The work addresses only the case of transporting dangerous goods.

It is time-consuming or impossible to investigate the robustness of a particular algorithm for identifying danger in general by using this approach. The algorithm is desirable that could as accurately as possible indicate the conditions for unacceptable results from assessing the danger of objects.

3. The aim and objectives of the study

The aim of this study is to construct an algorithm to build regions in the space of dangerous factors, in which solutions from existing algorithms for determining hazards emanating from industrial facilities containing combustible gases are critically unreliable.

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

– to propose mathematical algorithms based on the use of *R*-functions to form hazard criteria for industrial facilities containing combustible gases;

– to define the limits for change in hazards for the case of combustible gases;

– to suggest ways to identify instances of inapplicability of algorithms for determining dangers emanating from industrial facilities that contain combustible gases;

– to perform numerical experiments in order to verify the proposed mathematical algorithms for individual cases.

4. Defining crucial criteria to assess dangers from industrial devices

Indicator functions. According to regulations that define the explosiveness of the premises or an outdoor installation, the hazard assessment is carried out based on excess pressure of an explosion. Excess pressure of an explosion is considered dangerous if its value exceeds 5 kPa (at a distance of 30 m from the epicenter of the explosion for the case of an outdoor installation). Paper [5] accepted a magnitude P-5, where P is the amount of excess pressure in kilopascals, as a function of the hazard indicator. In this case, according to the indicator function, the object is dangerous if the value of the indicator is more than 0, if less than 0 – it is safe. Thus, we come to the emergence of a gradation of danger. It is allowed not to classify an installation plant as «A» provided that the amount of individual risk in the case of possible combustion of combustible substances with the formation of pressure waves does not exceed 10^{-6} per year at a distance of 30 m from the outdoor installation. The installation would be assigned to category B if the probability of death of a person (R) is greater than one millionth. Thus, the corresponding indicator function (indicator) will take the form:

$$R^R = R - 10^{-6}. \tag{1}$$

The indicator associated with the intensity of radiation will take the form:

$$I^R = I - I_0, \tag{2}$$

where $I_0 = 4$ kWm^{-2} (a threshold value).

A system of magnitudes based on p-functions [6] was used to determine the installation's belonging to a particular category of fire danger:

1) excess pressure ($P^R = P - 5$);

2) the horizontal size of the zone limiting gas-steam-air mixtures with the concentration of fuel above the lower concentration limit of propagation ($G^R = G - 30$);

3) fire load ($Q^R = Q - 180$);

4) radiation intensity ($I^R = (I - 4)$);

5) fire risk ($R^R = R - 10^{-6}$).

Criteria. It is possible to convert an indicator function into a criterion by dividing by the magnitude that has a dimensionality of the indicator function. In this case, there will be dimensionless magnitudes that accurately indicate the belonging of an object or a device to the class of dangerous:

1) $P^R = (P - 5)/1$ kPa;

2) $G^R = (G - 30)/1$ m;

3) $Q^R = (Q - 180)/(1\ \text{MJ}\cdot\text{m}^{-2})$;

4) $I^R = (I - 4)/(1\ \text{kW}\cdot\text{m}^{-2})$;

5) $R^R = R - 10^{-6}$.

By using p-functions, we shall define the most used criteria. First, we shall determine a common criterion of danger:

$$A^{PGR} = A^{PG} + A^R + \sqrt{\left(A^{PG}\right)^2 + \left(A^R\right)^2}, \tag{3}$$

$$A^{PG} = A^P + A^G + \sqrt{\left(A^P\right)^2 + \left(A^G\right)^2}, \tag{4}$$

where A^P, A^G, A^R are the criteria for relevant indicator functions; PG, A^{PG}, A^{PGR} are the criteria corresponding to the case of positive values of several indicator functions at once.

Formulae (3), (4) allow us to strictly describe to a large extent verbally assigned algorithms of regulations.

5. Boundaries of the interval, which may contain numerical values of dangerous properties of all known combustible gases

Next, we shall consider the behavior of the criteria over intervals, which may contain numerical values of properties of all known combustible gases. Any dangerous substance is represented in mathematical algorithms to assess the danger of an object by a single set of numerically expressed dangerous properties (or influencing the danger), and by this set only. In fact, these properties will be included into a set of factors that affect danger and become part of the factor space. It is obvious that these properties have some connection with each other. Some of their combinations are not feasible, others are rare or their existence is unlikely. We shall consider these properties to be magnitudes independent of each other. This will provide an opportunity to address the issue on gas danger from some common positions. Let us numerically determine the limits of intervals, which may contain the numerical values of these factors (properties of all known combustible gases, vapors of flammable liquids, their mixtures in different combinations).

Gas density (ρ) under normal conditions is proportional to its molar mass with good accuracy. Therefore, the density of the heaviest known radon gas (atomic mass 222) is about 110 times the density of the lightest hydrogen gas, 0.00008988 (at 20 °C), g/cm^{-3}. Density will be considered in the range of 0.09–19.90 kgm^{-3}. For gas density under normal conditions, the hazard criterion G^R is the horizontal size of the zone that limits gas-vapor mixtures with a concentration of fuel above the lower concentration limit of flame propagation. Other criteria do not respond to gas density within the algorithm studied. The horizontal size of the zone is minimal at the maximum value of gas density (Fig. 1) (hereafter calculations are performed in exact accordance with mathematical algorithms in the acting regulations of Ukraine).

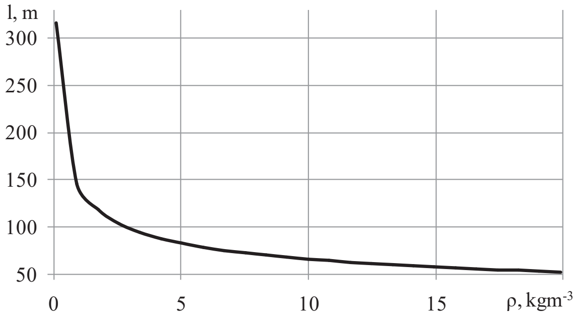

Fig. 1. Dependence of the horizontal size of zone (l) limiting gas-vapor-air mixtures with fuel concentrations above the lower concentration limit of flame propagation, on gas density under normal conditions (ρ)

Specific heat of combustion (Q) of pyrolysis gas is 12 MJkg^{-1}; hydrogen, 141 MJkg^{-1}. We shall consider these values as the lowest and greatest possible values of specific combustion heat, that is the limits of change in this value are 12–141 MJkg^{-1}.

Dependences of the examined parameters on the specific heat of combustion are shown in Fig. 2, 3.

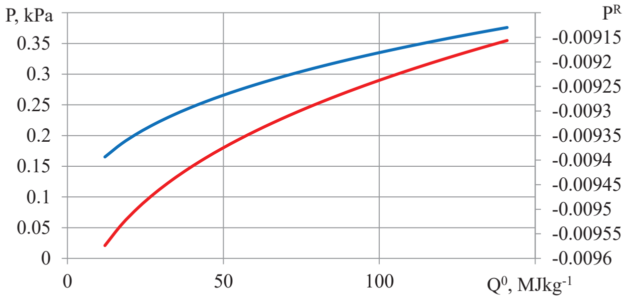

Fig. 2. Dependence of explosion excess pressure (P) and criterion (P^R) on specific combustion heat (Q^0): —— – excess pressure, kPa; —— – criterion P^R

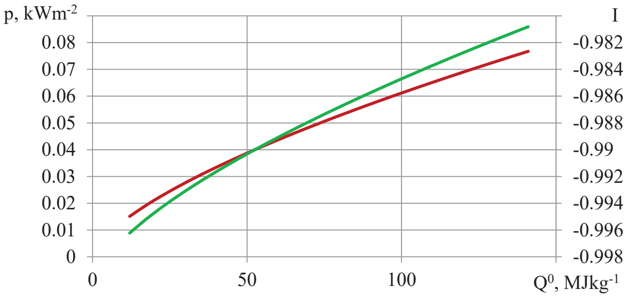

Fig. 3. Dependence of explosion pressure wave pulse (p) and criterion I on specific heat of combustion (Q^0): — – criterion I; — – explosion pressure wave pulse (p), kWm^{-2}

Participation rate Z is 0.1 to 1. It does not affect the horizontal size of the zone; however, it influences excess explosion pressure (Fig. 4), pressure wave pulse, risk of human death (Fig. 5).

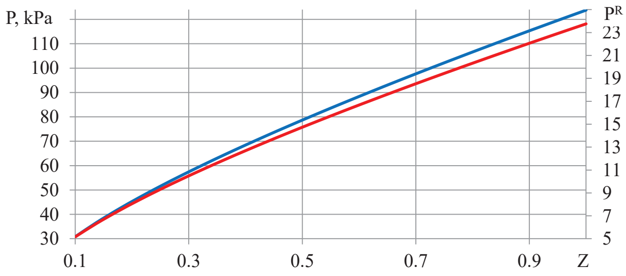

Fig. 4. Dependence of excess explosion pressure (P) and criterion P^R on participation rate Z: — – excess pressure, kPa; — – criterion P^R

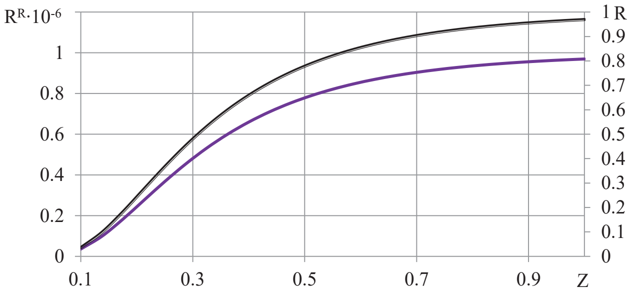

Fig. 5. Dependence of risk (R) and criterion P^R on participation rate (Z): — – risk; — – criterion P^R

The lower concentration limit of flame propagation (*LCLFP*) of butane is 1.9 % by volume, gasoline vapors, 0.8 % by volume. We would consider the possible range of LCLFP values in the interval between 0.008 and 0.400 of volume parts (v.p.) that affects only the horizontal size of the zone (Fig. 6).

The estimated temperature of 10–60 °C affects only the horizontal size of the zone (Fig. 7).

Gas mass (m). With the remaining properties unchanged, there is such a threshold mass of gas at a facility that, if it is exceeded, this facility would relate to the dangerous ones of appropriate level. Dependences of hazard criteria on gas mass are shown in Fig. 8.

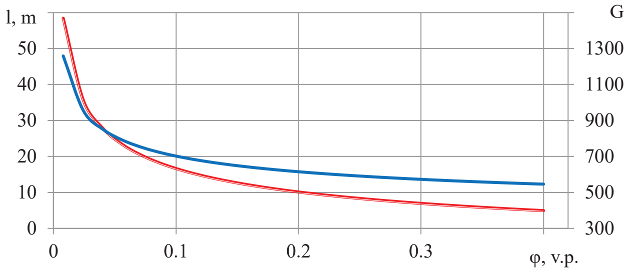

Fig. 6. Dependence of the zone's horizontal size (l) and criterion G on LCLFP (φ): — – criterion G; — – horizontal size of the zone limiting gas-vapor-air mixtures with a concentration of fuel above LCLFP

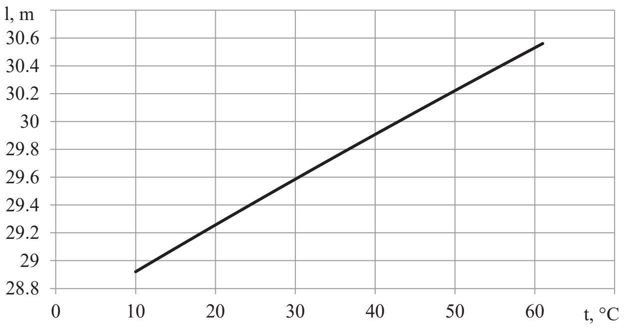

Fig. 7. Dependence of the zone's horizontal size (l) on estimated temperature (t)

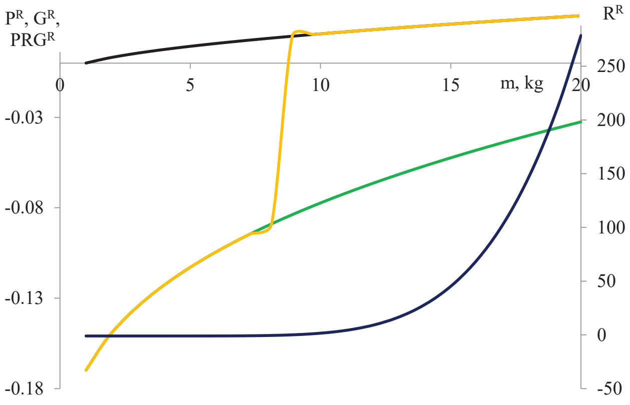

Fig. 8. Dependence of relevant criteria on gas mass (m): — – criterion P^R; — – criterion G^R; — – criterion PRG^R; — – criterion R^R

As shown by graphs in Fig. 1–8, for some properties of substances the minimum danger is achieved at a minimum numerical value of the property, for others – at the maximum. This fact divides the properties of substances (dangerous factors) into two categories. Fig. 8 shows the complex character of these dependences.

6. Analysis of hazardous objects in a factor space

Let us consider an object consisting of a single container that contains gas. Its danger will be determined by a set of numerically assigned properties (factors determining the danger) of gas, its quantity and storage conditions. Let us call such an object elementary. An object can be represented by a vector whose components are the specified factors.

By varying the components of the vector, we obtain an infinite number of elementary objects. The totality of vector-objects will make up the vector or factor space of dangerous elementary objects. The regulatory literature, responsible for the safety of life activities, offers a set of mathematical algorithms to determine the criteria for the danger of an object. As a result, each object is matched with a set (vector) of hazard criteria. This means that each specific mathematical algorithm from the above regulations is matched by an operator converting a set of factors (object-vector) into a vector of criteria:

$$\vec{a}=E\left(\vec{f}\right), \tag{5}$$

where $\vec{a}$ is the vector of criteria; $\vec{f}$ is the vector of factors corresponding to a dangerous object. For an elementary object, there will be $\vec{a}=\left\{P^R,\ G^R,\ Q^R,\ R^R,\ I^R, A^P, A^G, A^{PG}, A^{PGR}\right\}$, vector-criteria, and there will be $\vec{f}=\{\rho,\ Q,\ Z, LCLFP,\ t,\ m\}$ vector-factors.

Thus, each elementary object within a factor space is matched with several criteria of danger (hazard vector). Thus, we obtain a vector field of dangers. A vector field can be converted into a scalar field by highlighting one of the hazard criteria, or, by using a *p*-function technology, one can convert part or all of the hazard vector factors into a single scalar. We shall map a multidimensional factor space into a three-dimensional space. To this end, we shall highlight three hazardous factors by giving permanent importance to other factors corresponding to the minimum danger in the examined region of changes in hazardous factors in (unless explicitly stated otherwise). The three-dimensional scalar field will be split into negative and positive parts, each of which would contain, respectively, non-dangerous and dangerous elementary objects. Elementary objects within this space are represented either by vectors or points, depending on the representation that is more convenient in a particular case. Thus, the space of dangerous elementary objects will be divided into dangerous and not dangerous parts or regions.

At a minimum gas density of 0.09 kg/m^3 and a gas mass of 0.6 kg, the space of dangerous elementary objects is split by the next boundary into dangerous and non-hazardous parts (Fig. 9).

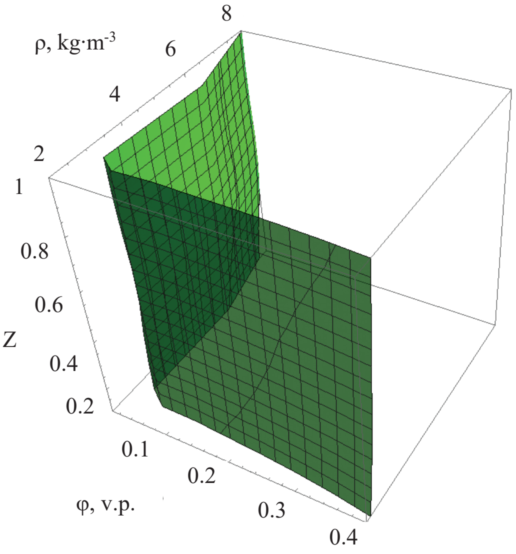

Fig. 9. Interface boundary of space with dangerous and non-hazardous objects: ρ – gas density, kg·m^{-3}; *Z* – gas participation rate in the combustion reaction; LCLFP – lower concentration limit for flame propagation, v.p.

Next, for better visualization, the results from our study are represented in the form of regions filled with dots (Fig. 10). The region filled with dots contains dangerous objects.

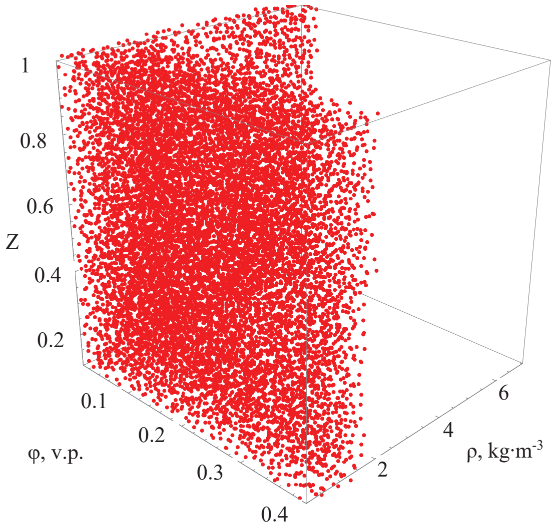

Fig. 10. Interface boundary of space with dangerous and non-hazardous objects: ρ – gas density, kg·m^{-3}; *Z* – gas participation rate in the combustion reaction; LCLFP – lower concentration limit for flame propagation, v.p.

Thus, a dangerous area of the factor space is highlighted. The region of the factor space filled with dots in Fig. 10 is the region with dangerous objects.

7. Determining a region of questionable decisions

The sensitivity of a regulation document (regulatory document algorithm) is due to the *sensitivity of its algorithm*, that is, the ability to significantly change the results of its application at a change in the original data. Let us see how sensitive the danger criteria are to a change in factors. In contrast to work [8], we shall evaluate the sensitivity of the relevant mathematical algorithm not based on a change in some calculated final characteristic, but based on the existence and character of location of the region of questionable decisions.

The region of questionable decisions will designate the area within a factor space, in which due to the inaccuracy of original data it is possible to make two mutually exclusive decisions: the object is dangerous and the object is safe. The region of questionable decisions should be determined from the condition: $s>0$, for all possible values of $\Delta\vec{f}$ within the limits of all possible changes for each component, where *s* is the criterion of belonging to the region of questionable decisions.

$$s=\begin{cases} P(\vec{a}), & \text{if } P(\vec{a})>0,\ \vec{a}=E\left(\vec{f}\right) \text{ and } P\left(E\left(\vec{f}+\Delta\vec{f}\right)\right)<0,\\ -P(\vec{a}), & \text{if } P(\vec{a})>0 \qquad\qquad\quad \text{ and } P\left(E\left(\vec{f}+\Delta\vec{f}\right)\right)>0,\\ -P(\vec{a}), & \text{if } P(\vec{a})<0 \qquad\qquad\quad \text{ and } P\left(E\left(\vec{f}+\Delta\vec{f}\right)\right)>0,\\ P(\vec{a}), & \text{if } P(\vec{a})<0 \qquad\qquad\quad \text{ and } P\left(E\left(\vec{f}+\Delta\vec{f}\right)\right)<0, \end{cases} \tag{6}$$

where there are $\vec{a}=\left\{P^R,\ G^R,\ Q^R,\ R^R,\ I^R,\ A^P, A^G, A^{PG}, A^{PGR}\right\}$ vector-criteria; $\vec{f}=\{\rho,\ Q,\ Z, LCLFP,\ t,\ m\}$ vector factors; $\Delta\vec{f}$ is the vector characterizing the accuracy with which $\vec{f}$, is known or another characteristic corresponding to a possible change in $\vec f$.

$P(\vec a)$ is the operator, which, based on numerical values for components $\vec a$, generates a positive numerical value in the event that the object is dangerous and negative otherwise. In the following examples, $P(\vec a)$ will take the following simple form:

$$P(\vec a) = A^{PRG}. \tag{7}$$

Each specific mathematical algorithm for any regulation document is assigned with the operator that converts a set of factors (object-vector) into vector-criteria:

$$\vec a = E(\vec f), \tag{8}$$

where $\vec a$ is the vector of criteria; $\vec f$ is the vector of factors corresponding to a dangerous object. In the case of categorization, for an elementary object, there will be $\vec a = \{P^R,\ G^R,\ Q^R,\ R^R,\ I^R,\ A^P, A^G, A^{PG}, A^{PGR}\}$, vector-criteria and $\vec f = \{LCLFP,\ \rho,\ Z, Q,\ t,\ m\}$ vector-factors.

The uncertainty interval in the lower concentration limit for flame propagation will be accepted as LCLFP±0.008, or from LCLFP−0.0001 to LCLFP+0.0001. The uncertainty interval in density will be taken as ρ±0.01. The uncertainty interval in the participation rate is Z±0.1 Let us specify the uncertainty in the vector factor without showing the components constants:

$$\Delta\vec f = \{\Delta LCLFP, \Delta\rho,\ \Delta Z\} = \{0.008;\ 0.5;\ 0.3\}. \tag{9}$$

This uncertainty of the raw data leads to the form of a region of questionable decisions presented in Fig. 11.

For comparison, at

$$\Delta\vec f = \{\Delta LCLFP,\ \Delta\rho,\ \Delta Z\} = \{0.0001;\ 0.01;\ 0.1\},$$

the region of uncertainty will take the from shown in Fig. 12.

Reducing the region of uncertainty within $\Delta\vec f$ leads to a decrease in the area of uncertainty region in the space of dangerous factors. Fig. 12 qualitatively characterizes the dependence of uncertainty in the results from determining the danger of an industrial device on the uncertainty in the original data.

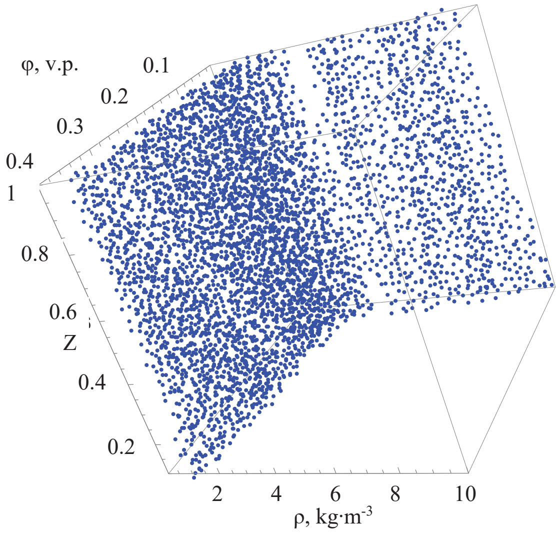

Fig. 11. Uncertainty region at $\Delta\vec f = \{\Delta LCLFP,\ \Delta\rho,\ \Delta Z\} = \{0.008;\ 0.5;\ 0.3\}$

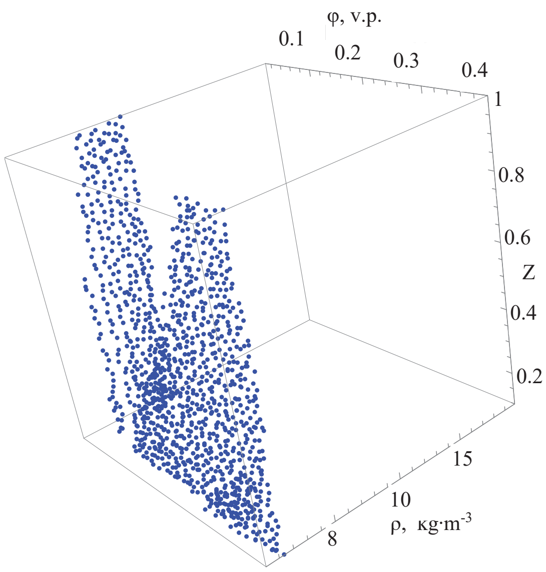

Fig. 12. Uncertainty region at $\Delta\vec f = \{\Delta LCLFP,\ \Delta\rho,\ \Delta Z\} = \{0.0001;\ 0.01;\ 0.1\}$

8. Discussion of results of studying the reliability of existing methods for determining hazards of production facilities

The current research is continuation of previous studies reported, for example, in [9]. Earlier studies were carried out statistically on simulation models. There were different source data that caused random changes in hazard criteria. Based on statistical research, the authors evaluated the likely error in the results from determining hazards at facilities. The use of stochastic methods in conjunction with simulation modeling has made it convenient to assess the robustness of a mathematical algorithm for determining dangers emanating from objects. That has made it less time-consuming and, therefore, affordable to compare different versions of algorithms. Thus, paper [9] compared algorithms for determining the danger of outdoor installations in 3 countries: Ukraine, Belarus, and Russia. Fig. 1–9 of the cited paper [9] show graphs of dependences of hazard criteria defined for the case of a specific production plant, examined in the study, on the hazard factors selected for that case. The graphs were built at constant values of other dangerous factors. It is obvious that these graphs can change at a change in other hazards. Fig. 9–12 of our work give an idea of how the pattern of stability would change when a third factor is added (the complete analogy with paper [9] is not relevant since paper [9] considered another industrial device utilizing other substances). The location of the interface boundary of the area with dangerous and non-dangerous objects in Fig. 9, 10 has a three-dimensional change. The region of uncertainty (Fig. 11, 12) changes not only its location, but its specific volume as well (specific volume refers to the ratio of the volume of an uncertainty region to a certain fixed volume, which covers the interface boundary between dangerous and not dangerous regions, in different places within a space of dangerous factors). It is obvious that the region of questionable decisions would change when other dangerous factors change.

Appropriate criteria have been devised based on R-functions for production facilities containing combustible gases. The existence of a region of questionable decisions is associated with the natural property of mathematical algorithms for regulation documents, termed robustness to the inaccuracy of original data, which determines the applicability of a regulatory document in specific cases. The algorithm described in formulae (6) to (8) allows the three-dimensional detection and visualization of the region of questionable decisions. Geometric consideration of an uncertainty region depending on dangerous factors whose quantity is larger than three is impossible, due to the impossibility to graphically display a space that has more than three dimensions, which requires fundamentally new ways to evaluate regulatory documents in terms of their visual representation. Ways in which regulatory documents are evaluated and visually represented is a subject of serious further research. Such studies may create a common method for assessing the quality of regulations.

The maximum limits to intervals, which may contain the numerical values of dangerous properties for all known combustible gases, have been defined. In each case of a hazardous production, these limits must be narrowed taking into considerations the characteristics of a particular industrial facility, appropriate technological and natural conditions.

9. Conditions

1. The use of p-functions allows the formation of complex criteria for dangers in the form of a single analytical expression. Applying a single analytical expression allows for a relatively simple way to separate and investigate potentially dangerous objects with flammable gases in the space of hazardous factors. Within the framework of this study, we have managed to construct algorithms that take a unified approach to defining the area of decisions. The essence is a technique to determine a region of questionable decisions, which is visible visually, but its size is not quantified for the time being.

2. In the space of hazardous factors, there is a vast area with potentially dangerous objects in which the probability of making an erroneous decision is not determined and is not assumed to be of magnitude that is less than the likelihood of making a proper decision. This area is called the region of questionable decisions. The region of questionable decisions can be complex. The boundaries and volume of the region of questionable decisions depend on the device and phenomena occurring at a production facility.

3. Determining whether an object belongs to the region of questionable decisions is a uniquely solvable numerical problem. We have proposed an approach for determining whether a factor space belongs to the region of questionable decisions.

4. At this stage of research, the results from numerical experiments show the existence of a significant volume of the region of questionable decisions. At the same time, the systematization of regions of questionable decisions and the magnitude of their volumes is a laborious and complicated affair. However, it can be stated that any other technique to create objects' hazard criteria would imply using a *R*-function method in the implicit form. Thus, any approaches to assessing the robustness of mathematical algorithms of regulatory documents that define the danger of production facilities will be in one way or another similar to those proposed in our paper.

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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