Запропоновано модель для прогнозування параметрів вибухонебезпечного середовища на основі використання експертних висновків у випадку відсутності або недостовірності вхідних даних. Нейро-нечітка мережа, використана в якості моделі, може бути швидко перенавчена у разі уточнення концентрації вибухонебезпечної газопароповітряної суміші. Представлена технологія може бути використана в післяаварійний період для уточнення полів вибухонебезпечного середовища

Ключові слова: газопароповітряне вибухонебезпечне середовище, моделі і методи прогнозування, нечіткі дані, надзвичайна ситуація

Предложена модель для прогнозирования параметров взрывоопасной среды на основе использования экспертных заключений в случае отсутствия или недостоверности входных данных. Нейро-нечеткая сеть, используемая в качестве модели, может быть быстро переучена в случае уточнения концентрации взрывоопасной газопаровоздушной смеси. Представленная технология может быть использована в послеаварийный период для уточнения полей взрывоопасной среды

Ключевые слова: газовоздушная взрывоопасная среда, прогнозирование, нечеткие данные, раннее выявление чрезвычайной ситуации

UDC 004.89:519.878:614.834
DOI: 10.15587/1729-4061.2017.116839

FORECASTING THE EMERGENCY EXPLOSIVE ENVIRONMENT WITH THE USE OF FUZZY DATA

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1. Introduction

There are about 200 fires killing 2 people each year per every one hundred thousand people in the world, according to the Fire Statistics Center of the International Association of Fire and Rescue Services. 74 million fires, which killed 900 thousand people, happened during 19 years of observation. At the same time, statistics cover only 40–50 % of the planet's population. The problem of prevention and elimination of fires is relevant in Ukraine. A number of fires and severity of consequences rise in recent years. Rates of death per 100,000 population remains one of the highest rates in the world [1].

A danger to a person and his environment is constantly rising in a situation where thousands of potentially dangerous objects continue to function with worn, obsolete and fire-hazardous equipment. Especially dangerous are manufactures, where steam and air or gas and air clouds of explosive mixtures threaten with subsequent ignition.

Traditionally, prevention of the ignition of explosive gas and air mixtures (EGAM) starts in post-accident period, when a head of elimination of emergencies, feeling responsible, makes mistakes that have fatal consequences. Pre-accident forecasting and development of possible scenarios in case of an accident can reduce a negative psychological impact. That is why solution of problems of forecasting of explosions and consequences plays an important role in ensuring safety of the population and the environment.

Values of the lower and the upper concentration limits of ignition help to determine the possibility of a steam-air or gas-air explosion usually. Special established systems monitor a concentration of explosive substances continuously and inform the personnel of a dangerous situation adequately in order to prevent explosions at sites where such danger exists. One of the main elements of such systems is a sensor of concentration of substance (substances). Sensors are located on a territory (premises) in places where concentrations of EGAM may appear or at a certain distance from each other. The principle of operation of an explosion warning system is to control a concentration of an explosive gas-air mixture continuously and to provide warning signals when it reaches a certain critical value, usually less than the lower concentration limit of ignition. This approach makes possible to detect a fact of an accident, but at the same time it does not provide complete information on parameters of the explosive environment that was formed.

2. Literature review and problem statement

A considerable part of studies relates to the solution of a problem of forecasting of gas-steam-air explosive environment parameters. We can divide the mentioned works in two groups by two main directions: the first one relates to the establishment of the fact of an accident, the second one – to forecasting of parameters of the explosive environment and consequences of an explosion. At the same time, a number of works point to disadvantages of existing approaches to solution of mentioned problems. In particular, paper [2] established that there is a discrepancy in determination of a fire hazard of production processes and premises by indicators of the lower concentration limit of ignition and estimated values of excess pressure of an explosion.

Work [3] proposes a solution of the problem of explosion prevention for open territories. Authors of paper [4] show that it is not enough to use the fact of achievement of a certain limit concentration level only and offer additional use of a rate of growth for early detection of an emergency associated with a release of fire hazardous substances. Author of [5] proves that an important factor in solution of problems of explosions prevention in open technological installations, in particular in the oil refining industry, is a necessity to take into account places of possible stagnation of air masses. Explosive substances with a concentration above the lower limit of ignition can accumulate at such places.

Authors of papers [5, 6] found that a size and location of stagnation depend on weather and climatic conditions, in particular speed and direction of a wind. We do not doubt rationality of proposals, but we note that works [5, 6] do not indicate concrete models and technologies, which implement relevant ideas. We also noted an absence of results of determination of concentrations of an explosive gas-steam-air environment.

In addition to weather and climatic conditions, authors of paper [7] take into account critical parameters, for which there are no data, uncertainty in modeling and disadvantages in current US and European standard requirements for forecasting of steam ignitions. The mentioned studies do not take into account an option of clarifying of parameters of the explosive gas-steam-air environment. Thus, a head of elimination of emergencies will not have an opportunity to assess a situation objectively and make an appropriate management decision under critical conditions of an accident.

Authors point out a connection between weather conditions, an initial term and development of a cloud, which explodes, in a work [8]. They established that small leaks at very low winds might cause large incidents more likely than catastrophic failures that cause formation of a significant cloud of steam in all weather conditions. Authors of a work [8] draw attention to the presence of approximate methods for estimation of an area of gas-steam-air mixture, but they also note insensitivity of methods to concentration of gases in gas-steam-air mixtures [9].

In papers [10, 11], authors conducted research on the use of a neuro-fuzzy network with optimization by using EvoMax as a technology for a rapid search of acceptable or quasi-optimal values in the post-accident period in case of the outburst of dangerous chemicals. This gives possibility to clarify a concentration of dangerous chemicals in the air and initial values of parameters of an accident, to improve and objectify a decision-making process.

Authors of papers [2–9] focus on the establishing a fact of formation of an explosive gas-steam-air environment or forecasting of future events, but accuracy and correction of forecasts remain out of sight.

The unresolved part of the decision-making problem is a lack of reliable values of a concentration of explosive substance in the explosive gas-steam-air environment in the pre-accident period.

3. The aim and objectives of the study

The aim of present study is to increase the accuracy of forecasting of parameters of an explosive gas-air environment, which appears during accidents at potentially hazardous facilities.

We have to solve the following tasks to achieve the objective:

– formalized statement of the problem of identification of a concentration of EGAM in time as a dependence on external factors and determination of peculiarities of its solution;

– construction of a model for determination of a concentration of EGAM on the basis of expert conclusions;

– development of a technology for forecasting of parameters of an explosive gas-steam-air environment with a use of fuzzy data.

4. Materials and methods for forecasting the concentration of explosive gas-steam-air mixture using fuzzy data

Researchers use known methods of calculation to forecast a volume and amount of substance that can explode at a certain moment of time in an emergency associated with a release of EGAM.

Forecasting takes into account a number of factors including the main ones:

– mass of explosive substance in technological equipment (M);

– an area of a hole through which the release of explosive substance into the environment occurs (S);

– a parameter, which characterizes a position of a hole (H);

– air temperature (T);

– wind speed (V);

– wind direction (R).

If there is a spill of substance into a tray with subsequent evaporation during an accident, then we should take into account a height of a tray (H_p) also.

Forecasting with a use of calculations and linear models determines EGAM concentration after the start of the release. Main characteristics of such forecasting are: amount of explosive gas-steam-air substance in a cloud, a shape and area of a zone, where a concentration of explosive substance exists, in a range between the upper and lower concentration limits of ignition. It is difficult for a head of emergencies eliminations department to assess the situation objectively and to take the appropriate management decision to protect subordinate staff and the population and to minimize consequences of an accident under critical conditions of an accident. Thus, a significant informational uncertainty accompanies decision-making processes during the course of accidents with formation of an explosive environment. We propose to reduce the uncertainty in two stages. The first stage, during which we use expert conclusions, should occur in the pre-accident period. The second stage goes directly during the course of the release of explosive substance and the spread of a cloud.

Let us consider the simplest statement of the problem and the method of the solution.

Let us assume that an accident can occur on the territory of a particular enterprise (Fig. 1). The area

$$\Omega=\{(x,y)\,|\,x\in[A,B],y\in[C,D]\}$$

determines its spatial placement. We consider a coordinate z as a zero, as small enough comparing with values of plane coordinates. There is an area Θ inside the enterprise. An accident may occur at points of an area Θ,

$$\Theta=\left\{(x,y)\left|\begin{matrix}x\in(a,b),y\in(c,d),0\le a<A,\\ 0<b\le B,0\le c<C,0<d\le D\end{matrix}\right.\right\},$$

within this area, there are n sensors of an emergency detection system installed at x'_n, y'_n coordinate points within the mentioned area.

It is necessary to identify the dependence in the period preceding an accident:

$$C=f(P), \tag{1}$$

where C – is a concentration of explosive substance; P – is a vector of parameters and factors, which has the following structure:

$$P=(x_0,y_0,t_0,x'_n,y'_n,t,M,S,H,T,V,R),$$

where x_0, y_0, t_0 are coordinates of the point and time of an accident; (x'_n,y'_n,t) – are coordinates of the point, where a concentration of EGAM and corresponding time (both absolute or after the occurrence of an accident) are determined.

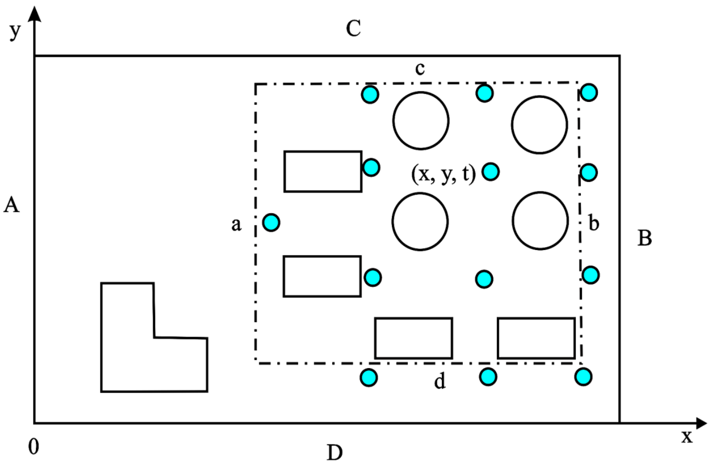

Fig. 1. Enterprise that has a possibility to form gas-steam-air explosive mixtures

By this statement of the problem, it is clear that there are parameters known before the start of the accidental release of explosive substance among elements of P vector. In particular, this is the data on the location of (x'_n,y'_n) concentration sensors and data that become known during an accident or forecasted by an expert (x_0, y_0, t_0, t, M, S, H, T, V, R). Let us present model (1) in a discrete-continuous form taking into account peculiarities of components of the vector

$$C=\begin{cases}f_1(Q), \text{ if } P_{const}\in H_1,\\ f_2(Q), \text{ if } P_{const}\in H_2,\\ \quad\ldots\\ f_n(Q), \text{ if } P_{const}\in H_n,\end{cases} \tag{2}$$

where P_{const} are components of P vector, their values are known precisely; $Q=P/P_{\text{const}}$ are elements of P vector, their values should be determined expertly.

Identification of $f_i(Q)$ functions is a prerequisite for a scenario analysis of possible actions [12] at different options of occurrence of accidents.

In a general case, let us assume that a number of factors, values of which are determined expertly and have different character, is equal to m. We denote X_1, X_2, ..., X_m. Let us consider the case when one expert makes conclusions about the importance of factor. Then the mathematical model of each of functions $f_i(Q)$ is a set of fuzzy production rules:

$$\begin{matrix}\text{If } x_1\in A_1^1\,\&\,x_2\in A_2^1\,\&\ldots\&\,x_m\in A_m^1, \text{ then } c\in C^1,\\ \text{else, if } x_1\in A_1^2\,\&\,x_2\in A_2^2\,\&\ldots\&\,x_m\in A_m^2, \text{ then } c\in C^2,\\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots,\\ \text{else, if } x_1\in A_1^k\,\&\,x_2\in A_2^k\,\&\ldots\&\,x_m\in A_m^k, \text{ then } c\in C^k,\end{matrix} \tag{3}$$

where k is a number of points of the experiment; A_i^j is a fuzzy set with a corresponding function of membership (FM) to the value of i-th factor in j-th experiment.

The initial data are the results of analytical calculations taking into account expert corrections of various kinds, tolerances and assumptions. The data table looks as Table 1.

Table 1

Output data table

Data amount	1	2	...	20
Wind speed, m/s	1	2	...	4
Wind direction, degrees	45	60	...	25
Air temperature, °C	25	–10	...	12
Substance mass, kg	7.46	12.4	...	69.2
Area of a hole, sm^2	10	5	...	15
Height of a hole, m	10	6	...	3
x_0	20	20	...	20
y_0	30	30	...	30
t_0	5	5	...	5
x	2,130	8,360	...	8,760
y	1,230	980	...	2,720
t	44	50	...	17
C	30	0.75	...	0.02

The nature of the source data and the type of the problem indicate the expediency of the use of Adaptive Network-Based Fuzzy Inference System (ANFIS) [13] for resolution and identification (1). We implement a fuzzy logical conclusion in Tsukamoto form in ANFIS. Functions of antecedent's membership are Gaussian with two parameters, FM of a consequent may be increasing, of

$$y=\sqrt{x},\quad y=x^n$$

type at the discretion of an expert. And

$$y=A+B\sqrt{x},\quad y=A+Bx^n,$$

where $y\in[0, 1]$.

When training a neuro-fuzzy network, we solve problems of parametric identification and find a value of parameters of all FM. The problem of identification requires significant time costs for data collection, analytical calculations and identification of the required dependence, so it has to be solved in the pre-accident period.

In case of an accident, it is sufficient to deliver values of parameters into the input of a model and obtain the value of the concentration of FM in any internal point of a fuzzy neural network training area.

A use of electrochemical and optical sensors is usually a base of a work of electronic gas analyzers. A list of substances that gas analyzers of emergency detection systems is limited [13], usually they are: Cl_2, F_2, O_3, O_2, H_2, SO_2, CO, CO_2, NO_2, NO, NH_3, H_2S, HF, HCl, PH_3, C_3H_8, C_6H_{14}, Σ of combustible hydrocarbons.

A change in concentration of a substance during measurement is not as significant for electronic devices as for photocolorimetric gas analyzers.

However, certain inertia in operation is characteristic due to the occurrence of physical phenomena (electrical conductivity, heat dissipation, etc.), the time of the output signal of a sensor can be from 15 seconds to 5 minutes.

Fig. 2 shows results of the experiment on definition of the inertia of the gas analyzer with a thermochemical sensor at determination of the concentration of methane in the air. A gas mixture of methane fled to the gas analyzer for 10 seconds, after which fresh air began to flow.

We can conclude from the results of the experiment that it is necessary to impose restrictions for the decision of concrete problems on the use of gas analyzers data, in particular:

– at concentrations exceeding a measurement range of gas analyzers, data indicate a fact of the occurrence of an accident and the location of a cloud only, it cannot be used to determine parameters of the explosive environment;

– due to the presence of inertia in the operation of gas analyzer sensors, it is necessary to preprocess them and exclude inertia data.

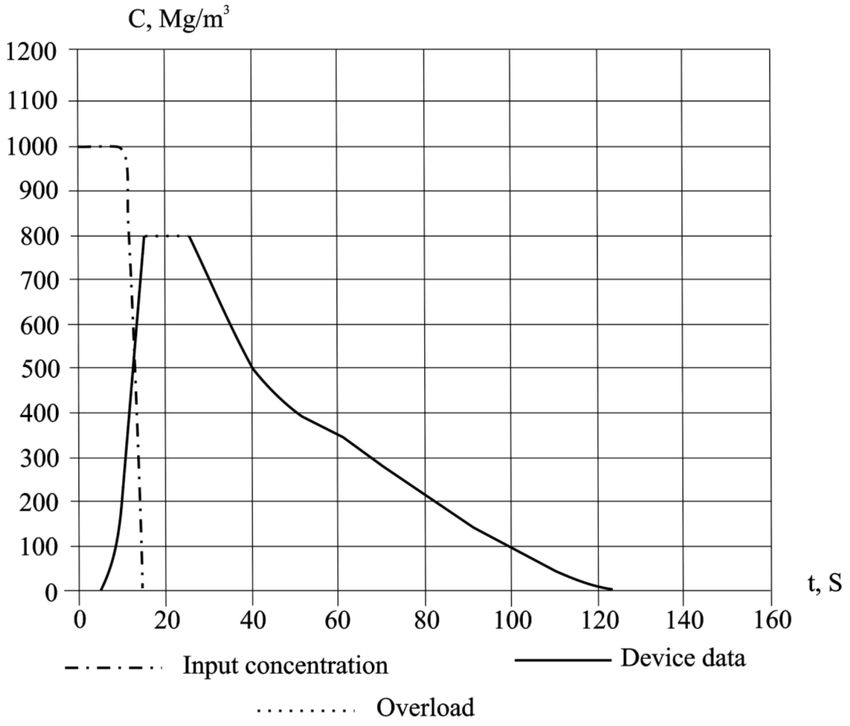

Fig. 2. Investigation of the operation of the gas analyzer with an electrochemical sensor at measurement of concentrations of methane in the air

5. Results of forecasting the parameters of an explosive gas-steam-air environment

Due to various reasons, it is difficult and sometimes impossible to determine values that characterize parameters of the gas environment immediately after an accident. Therefore, there is a high probability of receiving unreliable data based on results of calculations using a model (trained network ANFIS), where the output data are not precise, but predictable. Then, we determine a value of the concentration of EGAM at points of location of sensors of the emergency release detection system $A_i(x_i, y_i)$. We exclude values of concentration that do not meet conditions in this case:

$$C_i^n(A_i,t^j)>C_{\max},$$

$$C_i^n(A_i,t^j)-C_i^{n-1}(A_i,t^{j-1})/\Delta t>K_1,$$

$$C_i^n(A_i,t^j)-C_i^{n-1}(A_i,t^{j-1})/\Delta t<K_2, \tag{4}$$

where C_i^n is a fuzzy set from FM, which determines a concentration of EGAM in *j*-th experiment, $i=\overline{1,m}$, $j=\overline{1,k}$.

Let us choose a type of FM on a base of the following considerations and facts:

– *supp* $\mu_A(X)$ FM carrier contains a region of *X* values, that is $E(X)\subset supp\ \mu_A(X)$ and this ensures an adequate use of a fuzzy inference;

– a membership function can have trapezoidal or Gaussian appearance, which follows from the blurriness and non-criticalness of expert conclusions;

– a theorem on approximation by a fuzzy system of type (4) of any continuous function is proved (under the fulfillment of some additional conditions) [13] for a fuzzy logical conclusion in the form of a Mamdani with a use of Gaussian membership functions;

– if we use trapezoidal FM, then their parameters should be known.

We can use model (3) in two cases. In the first case, expert identified all FM structurally and parametrically, i.e. we know $\mu_{A_i^j}(x_i)$ and $\mu_{C^j}(c)$, $i=\overline{1,m}$, $j=\overline{1,k}$. Then, we can determine predictive value of the concentration as the resultant fuzzy set within FM by setting values $(x_1, x_2, ..., x_m)$ and using a fuzzy logic conclusion in the form of Mamdani.

$$\mu_C(c)= \\ =\max_j\{\min_i\{\mu_{A_1^j}(x_1),\mu_{A_2^j}(x_2),...,\mu_{A_m^j}(x_m),\mu_{C^j}(c)\}\}. \qquad (5)$$

The resulting function $\mathbf{m}_c(c)$ in its definition area is a broken line of sufficient complex form. Values reflect a confidence level of an expert at the level of concentration of EGAM. To localize and clarify an expert conclusion, it is necessary to make a de-fuzzification of a fuzzy value (a level of a concentration of EGAM) by the centroid method and obtain the most possible value:

$$c^*=\int_{c_1}^{c_2} c\mu_C(c)\mathrm{d}c \Big/ \int_{c_1}^{c_2} \mu_C(c)\mathrm{d}c, \qquad (6)$$

where $c_1=\min\{c/c\in \operatorname{supp}\mu_C(c)\}$, $c_2=\max\{c/c\in \operatorname{supp}\mu_C(c)\}$.

It is possible to determine a level of EGAM concentration at any possible point of the considered area if we identify dependencies (5), (6).

In the second case, FM are structurally identifiable, continuous, differentiated, but with unknown parameters. Gaussian functions often play role of such functions

$$f(x)=\exp\left[-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2\right],$$

where m and σ - are parameters. Such functions are present in antecedents of the model (3). It is not so clear with a consequent in this case as in the model (3). Since it is necessary to find FM for concentration values of explosive gas-steam-air mixture or the most possible value in the final analysis, the use of trivial, trapezoidal, Gaussian and similar functions is complicated in the consequent, as in these cases one or more values of an argument may correspond to one value of FM. The identified dependence can be defined ambiguously in such cases.

The most common solution for identification and forecasting problems is a use of fuzzy logic conclusion in a form of Mamdani, Tsukamoto, Takagi and Sugeno, Larsen and simplified logical conclusion [14]. The model (3) corresponds to a fuzzy logical conclusion in the form of both Mamdani and Larsen. They differ by the way of obtaining the function of belonging only $\alpha\wedge\mu_A(x)$ where $\alpha\in[0, 1]$.

In case of conclusion in the form of Mamdani

$$\mu_{\alpha\wedge\mu_A(x)}=\min\{\alpha,\mu_A(x)\},$$

for conclusion in the form of Larsen

$$\mu_{\alpha\wedge\mu_A(x)}=\alpha\cdot\mu_A(x).$$

FM of a consequent can be arbitrary in both cases. For a fuzzy conclusion in the form of Takagi and Sugeno, the consequent is a weighted sum of values of arguments of the antecedent. The mentioned features of the model do not make possible to use a fuzzy logical conclusion in the considered forms in the general case.

In the fuzzy logic conclusion of Tsukamoto FM of the consequent should be growing monotonically, which guarantees unambiguousness, as in the case of a simplified logical conclusion, where the consequent is a constant. Thus, we can use a simplified logical conclusion and conclusion in the form of Tsukamoto for the solution of the identification problem (1), (2).

We obtain the forecasted value of the concentration of EGAM immediately after receipt of the first data on the fact of an accident based on parameters, which are known and forecasted by experts. Then we determine a size of possible zones with concentrations within limits between the lower and upper concentration limits of ignition and calculate consequences of a possible explosion. Based on the data received, responsible persons take appropriate management decisions to prevent the explosion and human victims and reduce material damage in the event of an explosion, etc.

We should compare the forecasted value of concentration and values obtained from gas analyzers after some time interval Δt given by an expert, taking into account the constraints (A). $(C_{meas}-C_{ident})^2\leq\varepsilon$ where C_{meas} is a measured value, C_{ident} is an identifiable value, ε is a positive given number, then the forecasting results correspond to the actual situation at the object. Otherwise, when $(C_{meas}-C_{ident})^2>\varepsilon$, we can conclude that values of one or several parameters used in the forecasting do not correspond to the real situation.

We use heuristics to verify values of parameters:

1. The value of the concentration of EGAM, limits of the propagation of EGAM at temperature changes at a small value $T\pm\Delta T$ will not significantly change ($\Delta T\in(0,5)$, °C).
2. Reduce in a wind speed leads to an increase in the concentration of EGAM at the point of measurement and increase of the distribution zone.
3. Reduce in the filling level of a tank leads to a decrease in the concentration of EGAM in the distribution zone.
4. Reduce in the diameter of a hole of the depressurization reduces the value of the concentration of EGAM in the distribution zone.
5. Reduce in the height of a hole leads to an increase in the concentration of EGAM in the distribution zone.

We can reduce the last three heuristics to one. If there was less amount of combustible material in a tank, or the diameter of a depressurization hole was less, or the height of a depressurization hole was higher than the concentration of EGAM would be less predictable.

Let us assume that C_{meas} value is significantly different from C_{ident} value, which was obtained using the model. Since it is not possible to make an unambiguous conclusion by one measurement, due to several reasons that may lead to the obtained value, we need to conduct an additional study. Here are its main steps. Let us assume that it is possible to carry out two measurements at different points in time at one point of location simultaneously. We denote results of the measurements as C_{meas}^1 and C_{meas}^2, corresponding values are identified by the use of the model for the indicated points C_{mod}^1 and C_{mod}^2.

If $\left|C_{meas}^1-C_{meas}^2\right|=\left|C_{mod}^1-C_{mod}^2\right|$, then this is the evidence of the conservation of measurable and modeled increases of concentration. So, the assumption about a time of an accident is incorrect. To determine a direction of its correction we will write down production rules:

1\. If

$$(C^1_{meas} < C^1_{mod})\,\&\,(C^2_{meas} < C^2_{mod})\,\&\,(C^1_{mod} < C^2_{mod})\,\&$$
$$\&\,(C^1_{meas} \le C^2_{meas}),$$

then $V_e \,\&\, W_1$.

2\. If

$$(C^1_{meas} < C^1_{mod})\,\&\,(C^2_{meas} < C^2_{mod})\,\&\,(C^1_{mod} > C^2_{mod})\,\&$$
$$\&\,(C^1_{meas} < C^2_{meas}),$$

then $V_e \,\&\, W_2$.

3\. If

$$(C^1_{meas} > C^1_{mod})\,\&\,(C^2_{meas} > C^2_{mod})\,\&\,(C^1_{mod} > C^2_{mod})\,\&$$
$$\&\,(C^1_{meas} < C^2_{meas}),$$

then $V_e \,\&\, W_2$.

4\. If

$$(C^1_{meas} > C^1_{mod})\,\&\,(C^2_{meas} > C^2_{mod})\,\&\,(C^1_{mod} > C^2_{mod})\,\&$$
$$\&\,(C^1_{meas} \ge C^2_{meas}),$$

then $V_e \,\&\, W_2$.

If the increase in the concentration of EGAM varies significantly, then we apply the following rules:

5\. If

$$(C^1_{meas} = C^2_{meas} = 0)\,\&\,(0 < C^1_{mod} < C^2_{mod}),$$

then $(V_e \,\&\, W_1) \vee (V_v \,\&\, W_1)$.

6\. If

$$(C^1_{meas} = C^2_{meas} = 0)\,\&\,(0 < C^2_{mod} < C^1_{mod}),$$

then $(V_e \,\&\, W_2) \vee (V_v \,\&\, W_2)$.

7\. If

$$(C^1_{mod} = C^2_{mod} = 0)\,\&\,(0 < C^1_{meas})\,\&\,(0 < C^2_{meas}),$$

then $(V_e \,\&\, W_2) \vee (V_v \,\&\, W_2)$.

8\. If

$$((C^1_{meas} < C^2_{meas})\,\&\,(C^1_{mod} < C^2_{mod}))\,\&$$
$$\&\,(\left|C^1_{meas} - C^2_{meas}\right| < \left|C^1_{mod} - C^2_{mod}\right|),$$

then $(V_w \,\&\, W_1)\,\&\,(V_v \,\&\, W)$.

9\. If

$$((C^1_{meas} > C^2_{meas})\,\&\,(C^1_{mod} > C^2_{mod}))\,\&$$
$$\&\,(\left|C^1_{meas} - C^2_{meas}\right| < \left|C^1_{mod} - C^2_{mod}\right|),$$

then $V_w \,\&\, W_2$.

10\. If

$$(C^1_{meas} < C^2_{meas})\,\&\,(C^1_{mod} > C^2_{mod}))\,\&$$
$$\&\,(\left|C^1_{meas} - C^2_{meas}\right| < \left|C^1_{mod} - C^2_{mod}\right|),$$

then $V_v \,\&\, W_2$.

In rules 6, 7: V_e – «an accident occurred earlier», V_w – «amount of substance in a tank or a rate of its leakage was less», V_v – «a wind speed was less», W_i – «must use *i*-th part of the model, $i = \overline{1,2}$ ». Measurements must be made at the points t_1 and t_2, where arg max $C_{mod} < t_1 < t_2$ for the application of the second, third and eighth rules due to variability of a consequent. In the first two cases, it is necessary to check the implementation of production rules and make an appropriate decision; if for the eighth case conditions of rule 9 are met, then V_w takes place. Under conditions of the seventh rule, it is impossible to establish invariably whether V_e or V_w takes place.

Let us move on to modelling by following some simplifying assumptions without limiting the generalities. We remove the temperature from consideration (from model (1)) as the change in the temperature of air in a relatively small range slightly affects EGAM. We can take into account the direction of a wind through simple transformations if we know wind speed, coordinates of an accident point and coordinates of a point of measurement of concentration. Let us note that concentrations are often measured along a straight line passing through a point of an accident along the direction of a wind. Let us assume also that we know exactly the point of an accident.

Thus, we get the model in the form of a set of fuzzy production rules of the following type:

If

$$v \in V_i \,\&\, m \in M_i \,\&\, d \in D_i \,\&\, h \in H_i \,\&\, x \in X_i \,\&\, y \in Y_i \,\&\, t \in T_i,$$

then

$$c \in C_i, \;\; i = \overline{1,n}. \tag{7}$$

We considered conclusions of one expert about 20 variants of values of parameters-attributes of an accident and points of determination of concentration of dangerous substance to conduct experiments. The model of the identified dependence conditioned by rule 8 is the neuro-fuzzy network ANFIS [13]. Fig. 3 shows its structure 3. The choice of such a network is justified by peculiarities of the initial information and the problem. ANFIS functions in the following way.

Fuzzification of values of the factors goes in the neurons of the first layer:

$$z_j \to \mu_{Z_i^j}(z_j) = \exp(-(z_j - m_i^j)^2 / (\sigma_i^j)^2),$$

where *m* and **s** are parameters. We calculate values of truth parameters of each production rule 7 in the second layer:

$$\alpha_i = \min\{Z_i^1(z_1), Z_i^2(z_2), \ldots, Z_i^7(z_7)\},\; i = \overline{1,20}.$$

Next, we find the relative importance of the rules:

$$\bar{\alpha}_i = \alpha_i \Big/ \sum_{i=1}^{20} \alpha_i.$$

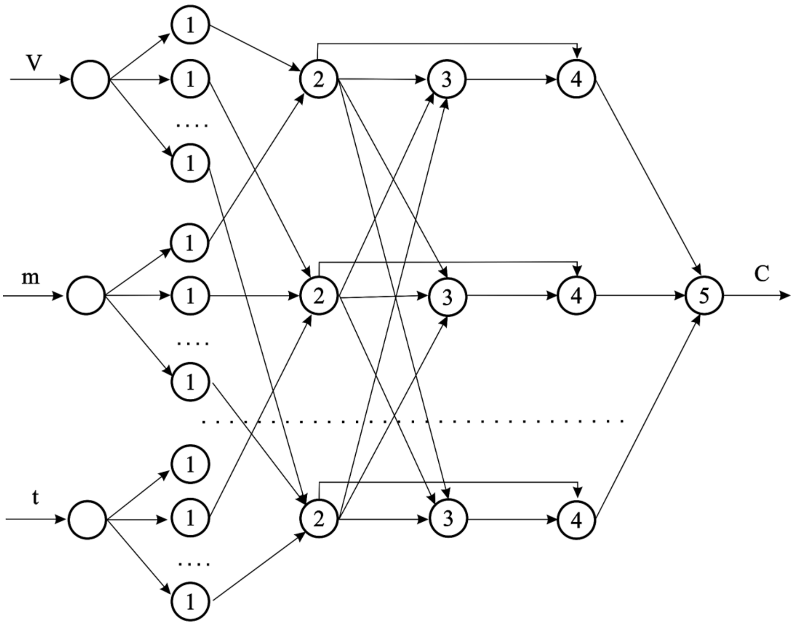

Fig. 3. Structure of ANFIS network with Tsukamoto conclusion algorithm

We count the product $\overline{\alpha}_i \cdot C_i^{-1}(c_i)$ and the neuron of the last layer, which is designed to find a sum, in neurons of the forth layer

$$\sum_{i=1}^{20} \overline{\alpha}_i \cdot \mu_{C_i}^{-1}(\overline{\alpha}_i).$$

It is known that concentration of dangerous substance increases to a certain point of time, and then it decreases. Therefore, as already mentioned above, a membership function of a consequent will be piecewise-continuous

$$\mu_{C_i}(c_i) = \begin{cases} \exp[-(c_i / \sigma_i)^2], \\ \text{if } t \in (0, \arg\max_t C(t, \text{const}), \ (W_1), \\ 1 - \exp[-(c_i / \sigma_i)^2] \ (W_2), \\ \text{if } t > \arg\max_t C(t, \text{const}), \ (W_2), \end{cases} \tag{9}$$

where the maximum concentration value should be searched for the time at constant values of other factors.

To study the neuro-fuzzy network ANFIS we selected:

– hybrid method (a combination of the least squares method with the reversed error propagation algorithm (GM)) [13, 14];

– a classic genetic algorithm with elite method of formation of a new population (GA) [15];

– a multidimensional analogue of Evo-Max (EM) method [16] based on the composition of evolution strategies [17];

– a method of elements of the theory of fuzzy sets [18];

– a method for analyzing a hierarchy of T. Saati [19].

Since a number of parameters whose values need to be determined is relatively large (about 300) in such a task, then experts set large part of them. In particular, we know values of all **s** parameters, as well as most of values of *m* for the antecedents, The remaining values of one *m* parameter in each 8-th rule remain unknown. The criterion for stopping all three algorithms was the fulfillment of the condition

$$\max_{i,j} \left| C_i - C_j \right| < 0{,}001, \tag{8}$$

in one population, where C_k is a concentration of EGAM, which corresponds to *k*-th potential solution (concentration of EGAM). The trained fuzzy neural network is a model by which it is possible to determine the concentration of EGAM at any point in the distribution region, if we know initial parameters of an accident. A model contains errors most often as source data for training goes from expert conclusions. Specialists go to a zone of EGAM distribution in the case of an accident, they measure concentration at least two times at one point (C_{meas}^1 and C_{meas}^2) after some time interval. Such a requirement exists due to the proposed method and the fact that devices – gas analyzers, are characterized by some inertia.

The results obtained have a character of a control sample. If there is a discrepancy between values measured and obtained using the model (C_{mod}^1 and C_{mod}^2), then we set a parameter, value of which we need to correct using the above production rules.

To do this, we fix experiment data except the value of the mentioned parameter and, correcting it (iter – a number of iterations), we seek the maximum coincidence of the «model» and the experimental value of the concentration. Then we correct all values of such parameter by the received value and re-train the network.

The modeling results are in Table 2, where σ is an average relative deviation (as a percentage) of measured and obtained by means of the model values of the concentration of EGAM.

We calculate values of the concentration of EGAM at two points of space or at one point, but at two different moments of time, using already trained model. We knew also the results of measurements of the concentration of EGAM at these points or at these moments of time. If the deviation of the simulated and measured values of the concentration of EGAM exceeds a certain value, then by means of the system of production rules (7), it is determined the value of which parameter of an accident were calculated incorrectly; we should correct this value re-train the neuro-fuzzy network.

Table 2

Modelling results

C_{meas}^1	C_{meas}^2	GM		GA		EM		GM		GA		EM	
		C_{mod}^1	C_{mod}^2	C_{mod}^1	C_{mod}^2	C_{mod}^1	C_{mod}^2	iter	C_{meas}^1	iter	C_{meas}^1	iter	C_{meas}^1
20	24	18	25	19	23	21	25	14	21	12	21	10	20.1
0.5	0.3	0.4	0.1	0.55	0.45	0.54	0.48	5	0.48	7	0.46	5	0.52
2	4	2.5	4.3	2.2	3.4	2.1	3.9	7	2.1	6	1.8	5	2.05
40	34	42	38	44	35	42	35	12	39	8	40.5	4	39
20	18	17	16	21	16	21.5	17.5	4	20	6	18.5	5	19.5
σ, %	–	15	–	8	–	6.1	–	–	3.3	–	6.4	–	2.4

6. Discussion of results of study of the technology of clarifying the concentration of explosive environment

Analysis of the simulation results indicates that EvoMax method is the most adequate model. Adjustment of this model is carried out, on average, for the shortest time and deviation of values obtained using the adjusted model from measured ones is the smallest. This result is expected, since the EvoMax is based on random but aimed search for an optimal solution implemented by means of protectionism for perspective solutions based on the values of the FM with a use of the hierarchy analysis method.

The proposed model can be used in information systems for forecasting of a zone of an explosive environment in case of accidents. It is based on the use of a neuro-fuzzy network and makes possible processing of expert conclusions and further processing and interpretation of results.

Taking into account the data of measurements of the concentration of EGAM by devices, a neuro-fuzzy network can be re-indexed in the shortest possible time and used to solve the problem of forecasting the concentration of EGAM at all possible points of the infected zone. In addition, the proposed technology can be used to clarify initial values of parameters of an accident, which will improve and objectify a decision-making process.

Accuracy of the solution of the problem of forecasting the consequences of accidents is a prerequisite for measures to save people, minimize material damage and prevent environmental disasters. Critical conditions for making decisions, features of each accident and the terrain, inertia of gas analyzers, and linearity of methods of calculation of concentration of EGAM are causes of ineffective forecasting. The application of the proposed post-forecasting technology for individual objects will make possible to refine models for determination of EGAM concentration, to improve the accuracy of forecasting with its use, and to determine initial values of parameters of an accident.

We should note that we presented the technology with some simplifications, in particular, a point of an accident is permanent and an expert made a wrong conclusion about the value of one parameter only. And although such assumptions, more often, take place in practice, the proposed approach can be applied in the general case with an increase in the number of production rules, the required measurement points and the time of simulation.

7. Conclusions

1. We proposed to set the problem of identification of a concentration of an explosive gas-air mixture in time with a use of expert conclusions based on the classification of methods for forecasting of emergencies. Its peculiarity is that we used fuzzy input data to solve the problem. We can get forecasted values in the form of fuzzy areas due to the solution.

2. A constructed model for determination of a concentration of EGAM gives possibility to forecast under condition of uncertainty. Expert conclusions made in the pre-accident period will be used during a real accident in the model. The proposed model will give possibility to estimate zones of explosive concentrations in the absence of a part of input data.

3. One can use the developed technology for forecasting parameters of an emergency explosive gas-air environment in the post-emergency period to clarify fields of an explosive environment. Taking into account data of measurements of a concentration of explosive gas-air mixture by devices, a neuro-fuzzy network can be retrained in the shortest possible time and used to solve a forecasting problem at all possible points in the zone of a gas-air explosive environment. In addition, one can use this technology to clarify initial values of parameters of an accident, which will improve and objectivize a decision-making process.

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