Запропоновано метод запобігання надзвичайним ситуаціям техногенного характеру унаслідок пожежі в приміщенні на основі використання поточної міри рекурентності приростів вектора стану газового середовища для виявлення можливих небезпек ураження обслуговуючого персоналу і руйнування обладнання в приміщеннях об'єкта. Дана міра дозволяє здійснювати оперативний контроль динаміки стану газового середовища і виявляти небезпечні стани, пов'язані з виникненням пожеж в приміщеннях об'єкта. Показано, що при виникненні небезпеки у вигляді пожежі газове середовище приміщенні є засобом передачі впливів від джерела займання. Проведена перевірка запропонованого методу на прикладі виявлення небезпеки у вигляді займань спирту і паперу в модельній камері, що імітує негерметичні приміщення об'єкта. Встановлено, що до моменту початку займання оцінка ймовірності рекурентності приростів станів газового середовища має тенденцію зростання від нуля до 0,5 для спирту і 0,6 для паперу. Відзначається, що тенденція зростання оцінки ймовірності рекурентності приростів станів газового середовища характеризується різкою і періодичною зміною зазначеної оцінки ймовірності. Виявлено, що до виникнення небезпеки, пов'язаної із займанням матеріалу, динаміка приростів характеризується випадковою зміною фазових станів, відповідних режиму динамічної стійкості. При виникненні небезпеки у вигляді загоряння матеріалу оцінка ймовірності рекурентності збільшень стає близькою до нуля. Ця ситуація відповідає втраті динамічної стійкості стану газового середовища. Після цього динаміка приростів характеризується окремими випадковими точками рекурентності, що належать області головної діагоналі рекурентної діаграми. Подальший розвиток даної небезпеки призводить до хаотичного характеру приростів станів газового середовища. Показано, що контроль динаміки приростів станів газового середовища дозволяє виявляти моменти виникнення небезпеки, пов'язаної із загорянням матеріалів в приміщеннях об'єкта. Це свідчить про працездатність запропонованого методу запобігання надзвичайним ситуаціям, пов'язаних з пожежами на об'єктах, шляхом раннього виявлення загорянь матеріалів на основі виявлення моментів, при яких відбувається зрив стійкості приростів станів газового середовища в приміщеннях

Ключові слова: надзвичайна ситуація, загоряння у приміщенні, поточна міра рекурентності, приріст станів, газове середовище, рекурентна діаграма

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A METHOD FOR PREVENTING THE EMERGENCY RESULTING FROM FIRES IN THE PREMISES THROUGH OPERATIVE CONTROL OVER A GAS MEDIUM

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1. Introduction

It is known that any emergency (E) occurs only in the case of the simultaneous presence of an object of danger (a danger) and a corresponding object of its impact. The world statistics indicate that the annual number of anthropogenic emergencies exceeds the number of annual emergencies of natural and another character by more than three times [1].

The acknowledged fact is that the main sources of anthropogenic emergencies are various types of potentially dangerous objects [2]. The results of long-term forecasting [3] and emergency statistics indicate a steady growth trend in emergencies, primarily due to an increase in the number of dangers. A danger, which affects an object of impact, leads to the human toll, damage to human health, destruction or annihilation of objects [4] and other material values, and also causes serious damage to the environment in case of emergencies [5]. We should note that humans themselves create prerequisites for the emergence of dangers, which entail emergencies, in the anthropogenic sphere. Therefore, a process of human interaction with the environment during production activities should minimize the risk of such dangers to avoid significant costs for the elimination of emergencies [6]. One of the important ways to reduce the risk of dangers is the implementation of measures to prevent possible emergencies. The implementation of emergency prevention methods makes it possible to reduce costs for the elimination of consequences by 2–3 times [7] and to reduce significantly or to avoid population loss completely. The world statistics indicate that causes of most anthropogenic emergencies are fires in the premises, which lead to injuries and death of personnel and significant destruction of technological equipment and premises, and facilities themselves. In this regard, the objective complexities of early detection of fires at facilities in the technical sphere, as well as the variety of potentially dangerous facilities, determine the expediency of prevention of emergencies caused by fires at facilities.

2. Literature review and problem statement

The gas environment of premises under conditions of danger is a complex system with a dissipative structure, non-linear dynamics, and self-organization. Classical methods are not able to identify existing complex relationships between elements in such a system, because a base of relationships is a series of linear principles that are usually violated [8]. This leads to false ideas about the real dynamics of the state of the gas environment in the premises in case of danger (fire) and does not give the possibility to carry out emergency prevention at facilities. However, nature of the dynamics of the state of the gas environment at the stage of the emergence of danger in the form of a fire is of paramount importance for prevention of injuring and death of maintenance personnel, as well as the destruction of technological equipment and units in the premises of facilities [9]. One should note that quantitative methods of nonlinear dynamics in the presence of noise and unsteady conditions are an active area for research in many disciplines at present [10, 11]. In particular, there are methods of time series analysis applied from the position of the theory of dynamical systems and fractal sets in geophysics [12]. However, it does not consider methods for the prevention of anthropogenic emergencies caused by fires at facilities. A base of the study of the process of emergence of fire in the premises is experimental data [13]. Paper [14] presents an assessment of the impact of thermal radiation on the rate of heat release in typical materials. Authors of work [15] carried out an experimental study on combustion modes for various materials under the external thermal influence [15]. Authors of work [16] investigated a rate of heat release during a fire in the premises. They note that the dynamics of the state of the gas environment in the premises at the stage of ignition of materials are complex, non-linear, and non-stationary. Work [17] investigates the increasing speed of known methods for the detection of fires in the premises. At the same time, it does not consider new methods capable of detecting changes in the state of the gas environment at ignitions and does not consider the dynamics of the states of the gas environment. It does not consider emergency prevention methods based on the detection of changes in the state of the gas environment. Authors of papers [18, 19] study self-adjusting methods for the detection of fires. However, the basis of self-adjusting methods is a series of averaged values of states of separate parameters of the gas environment only. They do not take into account and do not analyze the current dynamics of parameters of the gas environment during fires in the premises. The results presented in [20] show an analysis of the dynamics of the adaptive threshold and the probability of detection of fires only. There are no studies on the dynamics of states of parameters of the gas environment and their increments at the ignition of materials. There is no consideration of fire emergency prevention methods based on the analysis of increments of the state of the gas environment in the premises. An experimental study on temporal autocorrelation and pair correlations of the dynamics of the main parameters of the state of the gas environment at ignitions in a model premise is a subject of work [21]. Authors note that current indicators of structural features of the interaction and changes in parameters of the state of the gas environment, rather than their average values, are more important in the identification of fires in the premises. For example, there are known methods suitable for the identification of dangerous parameters of the gas environment in case of fire [22]. However, a base of the methods is a stationary approach, which makes it possible to determine only averaged energy indicators for parameters of the gas environment by lags and frequencies. The mentioned methods do not make it possible to take into account peculiarities of the time-frequency structure of the interaction of parameters of the state of the gas environment.

Work [23] considers methods of time and frequency localization. However, it notes that the problem of time-frequency localization remains unresolved. It indicates that the well-known methods are difficult to implement and unsuitable for the operative detection of fires in the premises and emergency prevention based on it. Due to the non-stationary nature of parameters of the state of the gas environment in the premises when ignition appears, work [24] considers a method based on the application of a Fourier transform to stationary fragments of the non-stationary dynamics of states. However, it is usually difficult to isolate sections of stationarity in the dynamics of the states of dangerous parameters of the gas environment at the identification of fires. The work does not consider and investigate the gas environment as a complex dynamic system, which generates a state of dangerous parameters in case of fires. Paper [25] is an experimental study of the dynamics of the burning rate of materials in closed and ventilated premises. However, there is no data on structural interactions of dangerous parameters of the gas environment at the ignition of materials in the premises. Work [26] studies increments of separate dangerous parameters of the gas environment as signs of fires. However, the results present the analysis of traditional statistical indicators of increments in parameters of the gas environment only. It does not consider the study of structural features of the dynamics of the states of the gas environment in the multidimensional phase space. Following [21–26], it states that fires are a source of disturbance of the initial equilibrium state of the gas environment in the premises of facilities. There are more complex nonlinear interactions of the main parameters of the state of the gas environment at ignitions.

Papers [27, 28] consider general methods for time-frequency identification of nonlinear dynamic systems. Work [29] describes a method for analysis of non-stationary process parameters based on a short-term Fourier transform. One should note that the methods considered in [27–29] turn out to be quite difficult to implement and we cannot consider them as constructive methods for the detection of fires in the premises and prevention of emergence of anthropogenic emergencies caused by fires. Papers [27–29] do not consider methods of nonlinear analysis of the system dynamics based on approaches other than the Fourier approach. Although in order to identify fires and develop methods for the prevention of emergencies caused by fires at facilities, it is necessary, first of all, to study a structure of the dynamics of the states and increments of the gas environment in multidimensional phase space. However, such results are not available in the available literature at the moment. Work [30] considers the application of the time-frequency method for the study of structural features of the dynamics of dangerous parameters of the gas environment at fires in the premises. It notes that the method is difficult to implement and it has insufficient efficiency. Moreover, the effectiveness of the method depends substantially on the type and parameters of the realized window functions used for averaging. In addition, the method, being an energy one, does not make it possible to study a structure of the dynamics of dangerous parameters of the gas environment in the corresponding phase space.

Thus, there are various time-frequency methods used to detect early fires in the premises due to the complexity of the dynamics of states and the interaction of dangerous parameters of the gas environment. However, the methods are complex and insufficiently efficient. They have limited detection sensitivity and scope. Therefore, their application to prevent emergencies caused by fires at facilities, using operative monitoring of the state of the gas environment in the premises, is problematic. Fractal methods of the nonlinear dynamics are more constructive and promising for the prevention of such emergencies [31]. A base of the methods is the use of current measures of recurrence of increments in the state of the gas environment in case of the emergence of danger in the form of a fire. Therefore, an important and unresolved part of the problem under consideration is the development of a method for the prevention of anthropogenic emergencies caused by fires at a facility based on the use of current measures of recurrence of increments in the state of the gas environment at fires in the premises.

3. The aim and objectives of the study

The objective of this study is to develop a method for the prevention of anthropogenic emergencies caused by fire applying operative monitoring of the state of the gas environment and using the current measure of recurrence of increments in the state of the gas environment in the premises.

We set the following tasks to achieve the objective:

– a system analysis of the emergence of anthropogenic emergencies caused by fire and possibility of prevention of them by monitoring of the state of the gas environment in the premises at a facility, as well as theoretical substantiation of the method for prevention of emergencies based on the estimation of the current measure of recurrence of increments in the state of the gas environment in the premises;

– verification of the efficiency of the method on the example of the state of the gas environment at the ignition of alcohol and paper in a chamber, which simulates a non-airtight placement of an object.

4. System analysis of emergencies caused by fire and substantiation of the method for their prevention

A base of the development of the method is the result of system analysis of the emergence of anthropogenic emergencies caused by fires in the premises at a facility and possibilities of application of the estimation of the state of the gas environment to prevent them. Let an arbitrary placement of an object represents some $S=O\bigcup E$, system, which consists of O danger object (a source of fire in the form of ignition of material), which is a potential source of emergencies, and $E=G\bigcup R$, environment where G is the gas environment of a premise, and R is the object exposed to an impact of a danger object (maintenance personnel, technological equipment, units and construction of a facility). O object influences R object through the gas environment of G premise in the system under consideration. $h\in O$ dangerous states characterize O object of danger. Such states can be, for example, ignitions of various materials or explosions of equipment and units in the premises. This means that we can describe O states at $t\in[0, T]$ time instants by $h=h(t)$ random function. $g\in G$ state also characterizes G gas environment of a premise, through which dangerous states are transferred from the source to an object of impact. In this case, parameters of the state of the gas environment can be, for example, factors of the gas environment that are dangerous for maintenance personnel. First of all, they are temperature, carbon monoxide concentration, and smoke density. $g=g(t)$ random function characterizes G state at various points in time. Finally, some $l\in R$ scalar parameter, which represents an amount of loss (damage) caused to R object by an impact of O object in general case, can characterize the state of R object exposed to an impact of an object of danger. $SG=O\bigcup G$ state of the system determines l parameter. It is some $l=l(h(t), g(t))$ functional.

However, $h=h(t)$ state of O object of danger determines $g=g(t)$ state of the gas environment in the premises $S=O\bigcup E$ system under consideration. Therefore, a current state of the gas environment in the premises will determine l parameter. For example, if the damage caused to R object depends on $g=g(x, t)$ state of dangerous factors of the gas environment at x point of a space of the object's placement, then we can represent l parameter as the corresponding one-dimensional integral function, which determines, for example, an inhalation dose of dangerous factors of the gas environment for maintenance personnel. Thus, prevention of an anthropogenic emergency caused by a fire at a facility is possible based on the current monitoring of $g=g(t)$ state of dangerous factors of the gas environment in the premises where technological equipment and maintenance personnel are located, taking into account losses caused to R object by an impact of O object.

$g=g(t)$ states of the gas environment in the premises depend not only on a source of danger. They are also subjects for various disturbances. There is no data on perturbations in most practical cases. The only information is measurements of the states of the gas environment taking into account perturbations [32]. Typically, a measurement of the state of the gas environment occurs at discrete time instants [33]. In general, we can represent the measurement information for i arbitrary discrete time instant by the m-dimensional vector of the state of dangerous factors

$$\bar{z}_i = \bar{d}_i + \bar{\Delta}_i, \quad i = 0, 1, 2, \ldots, N_S - 1, \tag{1}$$

where $\bar{d}_i$ is the vector of current states of the gas environment caused by danger; $\bar{\Delta}_i$ is the vector of current disturbances in the states of the gas environment; N_s is the size of a sample of measurements of the specified vector of the states.

Application of the RP method for the state vector (1) makes it possible to map trajectories of the state of the gas environment considered in the m-dimensional phase space onto a two-dimensional binary matrix of $N_s \times N_s$ size. A unit element of the matrix will correspond to the recurrent states (RS) of the gas environment at certain *i* and *j* instants of time and RP coordinate axes will be determined by the discrete measurement time. Following paper [31], one can represent the mapping mathematically by the following ratio

$$R_{i,j}^{m,\varepsilon} = \Theta\left(\varepsilon - \left\|\bar{z}_i - \bar{z}_j\right\|\right), \quad \bar{z}_i \in \Omega^m, \quad i, j = 1, 2, \ldots, N_S, \tag{2}$$

where Θ() is the Heaviside function; ε is the size of a neighborhood for $\bar{z}_i$ RS detection at *i* instant of time, and ‖*‖ is the operator of a norm calculation. The study of the dynamics of states of various complex systems based on (2) became popular due to the emergence of methods of quantitative RS analysis [34]. A basis of the methods is a series of appropriate measures, which give the possibility to measure the complexity of RP, which reflects special conditions in the systems under study numerically. Paper [35] proposes measures of recurrence of states for concentrations of atmospheric air pollution based on the use of (2). However, one cannot apply the well-known measures to prevent emergencies by monitoring the state of the gas environment in case of fire in the premises at a facility. The main limitation of the known measures is the insufficient efficiency in the detection of changes in the dynamics of the state of the gas environment at fires in the premises.

To ensure the efficiency of the recurrence measures developed in paper [35] and the possibility of application of them to detect changes in the dynamics of the state of the gas environment at fires in the premises, firstly, we propose to modify (2) in accordance with expression

$$TRP_{i,j}^{m,\varepsilon} = if\left(i \neq j \bigcap j \leq i, R_{i,j}^{m,\varepsilon}, 0\right). \tag{3}$$

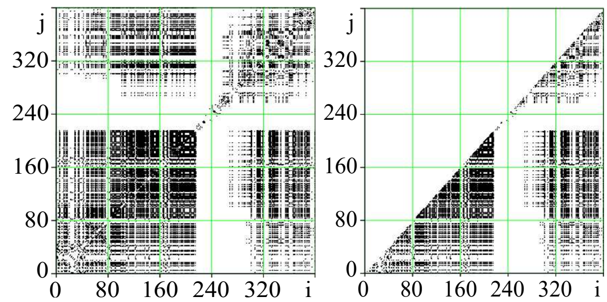
Expression (3) defines an operational method for calculation of RP in real-time observation in comparison with (2). One can propose the current measure of estimation of RS of the gas environment in the premises at a facility, based on the expression (3), by analogy with [34]. We determine it as follows

$$M_2(i, \varepsilon) = \frac{1}{i+1} \sum_{k=0}^{i} TRP_{i,k}^{m,\varepsilon}. \tag{4}$$

A measure (4) makes it possible to estimate RS for each current *i* time instant based on (3) and taking into account ε size of the neighborhood of recurrent states. The measure depends on ε size of the neighborhood, which should be selected from the condition of ensuring the authenticity of estimate (4) by real values of RS of the gas environment in the premises at a facility. This means that it is possible to identify the dynamics of repeatability of states in the current time using measure (4). The estimate (4) of RS characterizes the probability of the repeatability of states for the current moment in time numerically. It makes it possible to study features of the transition from stable states to unstable states in various dynamical systems. In this case, the operational estimation (4) can be a basis for the developed method for the prevention of anthropogenic emergencies caused by fires at facilities. We propose to calculate estimate (4) not for the states of the gas environment in the premises, but for increments of the states measured at the current and previous time points in order to detect changes in the dynamics of the state of the gas environment of premises effectively because increments of the states of the gas environment are more sensitive to fires in the premises. It was found that ignitions in the premises lead to a breakdown in the stability of precise increments in the state of the gas environment [36, 37]. One should note that in general, it is possible to forecast the moments, when the loss of stability of increments in the state of the gas environment in the premises caused by fires occurs, based on measure (4). In this case, it is possible to carry out forecasting at *i*+1 time instant from current observations up to *i* time, for example, by the method of exponential filtering or other methods. Thus, a base of the proposed method for the prevention of anthropogenic emergencies caused by a fire is the operative monitoring of the state of the gas environment in the premises at a facility using measure (4) for increments of the state of the gas environment. Fast detection of fires in the premises makes it possible to apply timely measures to eliminate them and prevent the development of an emergency, which poses a significant threat to the life of personnel, equipment, and destruction of premise structures.

5. Verification of operability of the method on the example of the state of the gas environment at the ignition of alcohol and paper in a model chamber

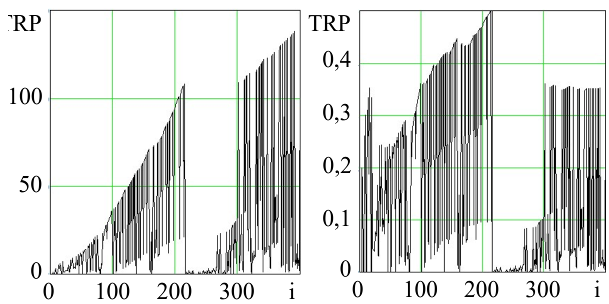
We carried out verification of the method for the prevention of anthropogenic emergencies caused by fire by real-time monitoring of the state of the gas environment in the premises based on the experimental data obtained at the ignition of alcohol and paper in a modeling chamber [30]. We measured components of the vector of the states of the gas environment in the chamber during the experiment. A concentration of CO, temperature, and smoke density determined them. We measured the mentioned states at t_i discrete time instants with Δt=0.1 second step for *i*=0, 1, 2, ..., 400. A counting number of *i* corresponded to t_i time instant of the interval of monitoring of the states of the gas environment. Therefore, $\bar{z}_i$. value determined the value of the state vector of the gas environment for counting of *i*. We ventilated the chamber naturally for 5–7 minutes before the ignition of paper. We set fire to alcohol and paper in the chamber in the region of 200 counts. We used TGS2442 (Japan), DS18B20 (Germany) and MQ-2 (China) sensors, respectively, as measuring tools for smoke density, temperature, and a CO concentration of the gas environment in the chamber. Fig. 1 shows RP of increments in the state of the gas environment determined by (2) and (3), for i=0, 1, 2, ..., 400 and j=0, 1, 2, ..., 400 at the ignition of alcohol in the modeling chamber at ε=0.01.



a *b*

Fig. 1. RP for increments of the states of the gas environment in the model premise at the ignition of alcohol: *a* – RP (2); *b* – RP (3)

Fig. 2 presents an illustration of the dynamics of a number and probability estimation of RS (4) for increments of the state of the gas environment at the ignition of alcohol in the model premise at ε=0.01.



a *b*

Fig. 2. The dynamics of RS of the gas environment at the ignition of alcohol in the model premise:
a – the number of RS;
b – estimate of the probability of RS determined by measure (4)

Fig. 3 shows RP for increments of the state of the gas environment in the model chamber in accordance with expressions (2) and (3) in case of danger caused by the ignition of paper in the model premise at ε=0.01.

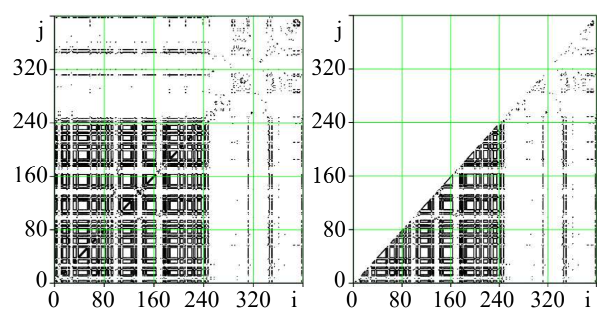
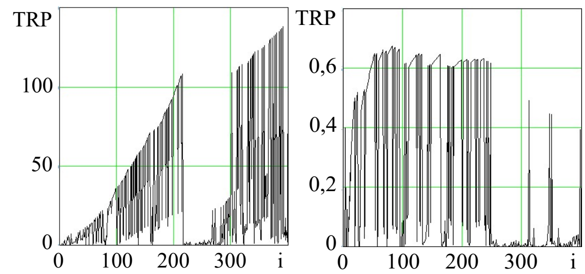


Fig. 3. RP for increments of the state of the gas environment in the model premise at the ignition of paper:
a – RP (2); *b* – RP (3)

Fig. 4 shows the dynamics of a number and estimation probability of RS (4) for increments of the state of the gas environment in case of the ignition of paper in the model premise at ε=0.01.



a *b*

Fig. 4. The dynamics of RS of the gas environment at the ignition of paper in the model premise: *a* – the number of RS; *b* – estimate of the probability of RS determined by measure (4)

We obtained the dependences presented in Fig. 1–4 taking into account real errors in the measurement of components of the state vector of the gas environment by sensors. One can assume that the presented data satisfy the corresponding degree of reliability within the limits of the methodological error, assuming that real modern fire detectors of various types are constructed based on the sensors used.

6. Discussion of results of verifying the method for prevention of emergencies caused by a fire in the premises

It follows from the analysis of RP in Fig. 1, 3 that the dynamics of increments in the state of the gas environment in case of a danger caused by the ignition of alcohol and paper in the model chamber is different.

The dynamics of increments of the states of the gas environment are similar and it shows a sharp change in stability over short time intervals until the moment of ignition of materials in the chamber. Such changes are characteristic of the conditions of dynamic equilibrium of the states of the gas environment in the premises in absence of ignition. There are some differences in RP in this interval in Fig. 1, 3 because the ignition of paper occurred after the ignition of alcohol with subsequent natural ventilation of a premise. There could be residual effects present in the gas environment. However, the similar nature of RP before the ignition indicates a sufficient degree of natural ventilation of the chamber. The white areas on RP indicate the absence of recurrence in increments of the states of the gas environment in the chamber. These areas characterize the loss of stability of the states of the gas environment and correspond to the moment of emergence of a danger caused by the ignition of alcohol and paper in the chamber. Further dynamics of increments of the state of the gas environment are chaotic because of the instability of the state of the gas environment. One can see fixed areas of the emergence of danger in Fig. 1, 3 (white areas of RP in the region of 200–250 counts). Therefore, one can state that given RP for increments in the state of the gas environment in general make it possible to identify the emergence of dangers in the form of ignitions of materials. The form of RP in Fig. 1, 3 are triangular, because we calculated RP in real-time, unlike RP in Fig. 1, 3, *a*. The triangular shape of RP corresponds to the operational calculation of RP. The use of these RP to calculate the proposed measure of recurrence of increments of the states (4), which is equal to the current estimate of the probability of repeatability numerically (Fig. 2, 4), indicates possibility of its application for identification of a danger at the start of the ignition of materials. Identification of the start of the ignition of the material makes it possible to warn about possible emergency if it will be not possible to eliminate fire by available means. Thus, the data presented in Fig. 1–4 indicate the efficiency of the developed method for the prevention of anthropogenic emergencies caused by fires at facilities using the operative monitoring of increments in the state of the gas environment in the premises.

The essence of emergency prevention is early detection of fires in the premises at a facility to eliminate fire and prevent emergencies, which cause death of personnel, failure of equipment and units, destruction of structures of premises and possibly an entire facility. We propose to control increments of the state of the gas environment in technological the premises at a facility for early detection of fires. Therefore, it is necessary to create a system for early detection of fires, which should relate to an automatic system for suppression of such fires in the premises at a facility. The main principle of the creation of a system for early detection of fires should be the operative control of increments of states of the gas environment based on the calculation of the proposed current estimation of their recurrence.

The results of the verification of the method are only experimental data on the ignition of materials in a model premise. One should note that in general, the sensitivity of the method will decrease with an increase in the distance of a corresponding sensor from a source of ignition. Therefore, it is advisable to place the sensor(s) in areas with the highest probability of fires in practical implementation. Typically, such zones in the technological premises of facilities are known. Therefore, we should consider further development of the study by conducting experimental verification of the operability of the method in real premises of facilities with various types of equipment. It is necessary to estimate the actual sensitivity and applicability limits of the proposed emergency prevention method, conditions for stability of results, and other indicators and parameters that affect the area of the practical application of the method in the course of such studies.

7. Conclusion

1. We carried out a systematic analysis of the occurrence of anthropogenic emergencies at facilities. It showed that it is possible to prevent emergencies based on monitoring of the state of the gas environment of premises for the operation of technological equipment and maintenance personnel. We showed that the gas environment in the premises at a facility serves as a means for the transition of dangerous impacts (carbon monoxide, temperature, and smoke) to an affected facility, which is a possible source of emergencies, in case of emergence of fires. We substantiated the method for the prevention of anthropogenic emergencies caused by fire in the premises theoretically using the current measure of recurrence of increments in the state vector of the gas environment. The proposed measure allows the operative monitoring of the dynamics of increments of the state of the gas environment and to identify dangerous states related to fires in the premises.

2. We carried out a verification of operability of the method for the prevention of anthropogenic emergencies caused by a fire on the example of the state of the gas environment at alcohol and paper ignition in a chamber, which simulated a non-airtight premise of an object. It was established that the estimation of the probability of recurrence of increments in states of the gas environment tended to increase from 0 to 0.6 before the ignition of alcohol and paper. A sharp and periodic change in the value of the estimation of the probability of recurrence accompanied the growth trend. It was revealed that increments of the states of the gas environment are random in nature, which corresponds to the mode of its dynamic stability, before the ignition of material. The estimate of the probability of recurrence of increments decreases sharply and approaches zero in case of the emergence of fires. The loss of dynamic stability occurs. Following the obtained results, the loss of dynamic stability occurs in the region of 200 counts. There are separate recurrence points randomly located in the region of the main diagonal of the recurrence plot in the dynamics of the recurrence of increments of states after ignition. We showed that then an unstable mode of increments of states of the gas environment comes. It indicates further chaotic development of ignitions. The obtained results indicate the efficiency of the proposed method for the prevention of emergencies caused by fire using the operative monitoring of parameters of the gas environment of the premises at a facility.

References

1. Kustov, M. V., Kalugin, V. D., Tutunik, V. V., Tarakhno, E. V. (2019). Physicochemical principles of the technology of modified pyrotechnic compositions to reduce the chemical pollution of the atmosphere. Voprosy khimii i khimicheskoi tekhnologii, 1, 92–99. doi: https://doi.org/10.32434/0321-4095-2019-122-1-92-99
2. Semko, A., Rusanova, O., Kazak, O., Beskrovnaya, M., Vinogradov, S., Gricina, I. (2015). The use of pulsed high-speed liquid jet for putting out gas blow-out. The International Journal of Multiphysics, 9 (1), 9–20. doi: https://doi.org/10.1260/1750-9548.9.1.9
3. Otrosh, Y., Kovalov, A., Semkiv, O., Rudeshko, I., Diven, V. (2018). Methodology remaining lifetime determination of the building structures. MATEC Web of Conferences, 230, 02023. doi: https://doi.org/10.1051/matecconf/201823002023
4. Kovalov, A., Otrosh, Y., Ostroverkh, O., Hrushovinchuk, O., Savchenko, O. (2018). Fire resistance evaluation of reinforced concrete floors with fire-retardant coating by calculation and experimental method. E3S Web of Conferences, 60, 00003. doi: https://doi.org/10.1051/e3sconf/20186000003
5. Semko, A. N., Beskrovnaya, M. V., Vinogradov, S. A., Hritsina, I. N., Yagudina, N. I. (2014). The usage of high speed impulse liquid jets for putting out gas blowouts. Journal of Theoretical and Applied Mechanics, 52 (3), 655–664.

6. Tiutiunyk, V. V., Ivanets, H. V., Tolkunov, I. A., Stetsyuk, E. I. (2018). System approach for readiness assessment units of civil defense to actions at emergency situations. Scientific Bulletin of National Mining University, 1, 99–105. doi: https://doi.org/10.29202/nvngu/2018-1/7
7. Dubinin, D., Korytchenko, K., Lisnyak, A., Hrytsyna, I., Trigub, V. (2017). Numerical simulation of the creation of a fire fighting barrier using an explosion of a combustible charge. Eastern-European Journal of Enterprise Technologies, 6 (10 (90)), 11–16. doi: https://doi.org/10.15587/1729-4061.2017.114504
8. Vasiliev, M. I., Movchan, I. O., Koval, O. M. (2014). Diminishing of ecological risk via optimization of fire-extinguishing system projects in timber-yards. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5, 106–113.
9. Kondratenko, O. M., Vambol, S. O., Strokov, O. P., Avramenko, A. M. (2015). Mathematical model of the efficiency of diesel particulate matter filter. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 6, 55–61.
10. Vasyukov, A., Loboichenko, V., Bushtec, S. (2016). Identification of bottled natural waters by using direct conductometry Ecology. Environment and Conservation, 22 (3), 1171–1176.
11. Pospelov, B., Andronov, V., Rybka, E., Meleshchenko, R., Borodych, P. (2018). Studying the recurrent diagrams of carbon monoxide concentration at early ignitions in premises. Eastern-European Journal of Enterprise Technologies, 3 (9 (93)), 34–40. doi: https://doi.org/10.15587/1729-4061.2018.133127
12. Turcotte, D. L. (1997). Fractals and chaos in geology and geophysics. Cambridge University Press. doi: https://doi.org/10.1017/cbo9781139174695
13. Poulsen, A., Jomaas, G. (2011). Experimental Study on the Burning Behavior of Pool Fires in Rooms with Different Wall Linings. Fire Technology, 48 (2), 419–439. doi: https://doi.org/10.1007/s10694-011-0230-0
14. Zhang, D., Xue, W. (2010). Effect of heat radiation on combustion heat release rate of larch. Journal of West China Forestry Science, 39, 148.
15. Ji, J., Yang, L., Fan, W. (2003). Experimental study on effects of burning behaviours of materials caused by external heat radiation. JCST, 9, 139.
16. Peng, X., Liu, S., Lu, G. (2005). Experimental Analysis on Heat Release Rate of Materials. Journal of Chongqing University, 28, 122.
17. Andronov, V., Pospelov, B., Rybka, E. (2017). Development of a method to improve the performance speed of maximal fire detectors. Eastern-European Journal of Enterprise Technologies, 2 (9), 32–37. doi: https://doi.org/10.15587/1729-4061.2017.96694
18. Pospelov, B., Andronov, V., Rybka, E., Skliarov, S. (2017). Design of fire detectors capable of self-adjusting by ignition. Eastern-European Journal of Enterprise Technologies, 4 (9 (88)), 53–59. doi: https://doi.org/10.15587/1729-4061.2017.108448
19. Andronov, V., Pospelov, B., Rybka, E., Skliarov, S. (2017). Examining the learning fire detectors under real conditions of application. Eastern-European Journal of Enterprise Technologies, 3 (9 (87)), 53–59. doi: https://doi.org/10.15587/1729-4061.2017.101985
20. Pospelov, B., Andronov, V., Rybka, E., Skliarov, S. (2017). Research into dynamics of setting the threshold and a probability of ignition detection by selfadjusting fire detectors. Eastern-European Journal of Enterprise Technologies, 5 (9 (89)), 43–48. doi: https://doi.org/10.15587/1729-4061.2017.110092
21. Pospelov, B., Rybka, E., Meleshchenko, R., Gornostal, S., Shcherbak, S. (2017). Results of experimental research into correlations between hazardous factors of ignition of materials in premises. Eastern-European Journal of Enterprise Technologies, 6 (10 (90)), 50–56. doi: https://doi.org/10.15587/1729-4061.2017.117789
22. Bendat, J. S., Piersol, A. G. (2010). Random data: analysis and measurement procedures. John Wiley & Sons. doi: https://doi.org/10.1002/9781118032428
23. Shafi, I., Ahmad, J., Shah, S. I., Kashif, F. M. (2009). Techniques to Obtain Good Resolution and Concentrated Time-Frequency Distributions: A Review. EURASIP Journal on Advances in Signal Processing, 2009 (1). doi: https://doi.org/10.1155/2009/673539
24. Singh, P. (2016). Time-frequency analysis via the fourier representation. HAL, 1–7. Available at: https://hal.archives-ouvertes.fr/hal-01303330
25. Pretrel, H., Querre, P., Forestier, M. (2005). Experimental Study Of Burning Rate Behaviour In Confined And Ventilated Fire Compartments. Fire Safety Science, 8, 1217–1228. doi: https://doi.org/10.3801/iafss.fss.8-1217
26. Pospelov, B., Andronov, V., Rybka, E., Popov, V., Romin, A. (2018). Experimental study of the fluctuations of gas medium parameters as early signs of fire. Eastern-European Journal of Enterprise Technologies, 1 (10 (91)), 50–55. doi: https://doi.org/10.15587/1729-4061.2018.122419
27. Stankovic, L., Dakovic, M., Thayaparan, T. (2014). Time-frequency signal analysis. Kindle edition, Amazon, 655.
28. Avargel, Y., Cohen, I. (2010). Modeling and Identification of Nonlinear Systems in the Short-Time Fourier Transform Domain. IEEE Transactions on Signal Processing, 58 (1), 291–304. doi: https://doi.org/10.1109/tsp.2009.2028978
29. Giv, H. H. (2013). Directional short-time Fourier transform. Journal of Mathematical Analysis and Applications, 399 (1), 100–107. doi: https://doi.org/10.1016/j.jmaa.2012.09.053

30. Pospelov, B., Andronov, V., Rybka, E., Popov, V., Semkiv, O. (2018). Development of the method of frequencytemporal representation of fluctuations of gaseous medium parameters at fire. Eastern-European Journal of Enterprise Technologies, 2 (10 (92)), 44–49. doi: https://doi.org/10.15587/1729-4061.2018.125926
31. Mandelbrot, B. (2002). Fraktalnaya geometriya prirodyi. Moscow, 656.
32. Marwan, N. (2011). How to avoid potential pitfalls in recurrence plot based data analysis. International Journal of Bifurcation and Chaos, 21 (04), 1003–1017. doi: https://doi.org/10.1142/s0218127411029008
33. Marwan, N., Webber, C. L., Macau, E. E. N., Viana, R. L. (2018). Introduction to focus issue: Recurrence quantification analysis for understanding complex systems. Chaos: An Interdisciplinary Journal of Nonlinear Science, 28 (8), 085601. doi: https://doi.org/10.1063/1.5050929
34. Webber, Jr. C. L., Zbilut, J. P. (2005). Recurrence quantification analysis of nonlinear dynamical systems. Tutorials in contemporary nonlinear methods for the behavioral sciences, 26.
35. Pospelov, B., Rybka, E., Meleshchenko, R., Borodych, P., Gornostal, S. (2019). Development of the method for rapid detection of hazardous atmospheric pollution of cities with the help of recurrence measures. Eastern-European Journal of Enterprise Technologies, 1 (10 (97)), 29–35. doi: https://doi.org/10.15587/1729-4061.2019.155027
36. Pospelov, B., Rybka, E., Togobytska, V., Meleshchenko, R., Danchenko, Y., Butenko, T. et. al. (2019). Construction of the method for semi-adaptive threshold scaling transformation when computing recurrent plots. Eastern-European Journal of Enterprise Technologies, 4 (10 (100)), 22–29. doi: https://doi.org/10.15587/1729-4061.2019.176579
37. Pospelov, B., Andronov, V., Rybka, E., Krainiukov, O., Karpets, K., Pirohov, O. et. al. (2019). Development of the correlation method for operative detection of recurrent states. Eastern-European Journal of Enterprise Technologies, 6 (4 (102)), 39–46. doi: https://doi.org/10.15587/1729-4061.2019.187252