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

B. Pospelov
Doctor of Technical Sciences, Professor*
E-mail: pospelov@ukr.net

R. Meleshchenko
PhD, Associate Professor
Department of Fire and Rescue Training**

O. Krainiukov
Doctor of Geographical Sciences, Associate Professor
Department of Environmental Safety and Environmental Education***

K. Karpets
PhD, Associate Professor
Department of Ecology and Neocology***

O. Petukhova
PhD, Associate Professor
Department of Fire Prevention in Settlements**

Yu. Bezhula
PhD
Department of Management and Organization Activities in the Field of Civil Protection**

T. Butenko
PhD, Senior Research*

V. Horinova
PhD*

P. Borodych
PhD, Associate Professor
Department of Fire and Rescue Training**

E. Kochanov
PhD
Department of Monitoring, Management of Natural Resources and Prevention of Emergency***
*Department of Organization and Coordination of Research Activities

Scientific-Methodical Center of Educational Institutions in the Sphere of Civil Defence
Chernyshevskaya str., 94, Kharkiv, Ukraine, 61023
**National University of Civil Defence of Ukraine
Chernyshevskaya str., 94, Kharkiv, Ukraine, 61023
***V. N. Karazin Kharkiv National University
Svobody sq., 4, Kharkiv, Ukraine, 61022

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 injuries 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. 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 parameters of the state of the gas environment. 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.

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 $SOE = \bigcup_j E_j$, 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 $E = \bigcup_j R_j$, 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. $heO$ 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 $O$ objects at $te[0, T]$ time instant by $h-h(t)$ random function. $gG$ state also characterizes $G$ gas environment of a premise, through which dangers 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 $hR$ 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. $SG = \bigcup_j G_j$ 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 $SOE = \bigcup_j E_j$ 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 a 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 an arbitrary discrete time instant by the m-dimensional vector of the state of dangerous factors

\[ \mathbf{z}_i = \mathbf{d}_i + \Delta \mathbf{z}, \quad i = 0, 1, 2, ..., N, -1, \quad (1) \]

where \( \mathbf{d}_i \) is the vector of current states of the gas environment caused by danger; \( \Delta \mathbf{z} \) is the vector of current disturbances in the states of the gas environment; \( N \) 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 \( N \times N \) 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

\[ R_{ij}^* = \Theta(\varepsilon - \| \mathbf{z}_i - \mathbf{z}_j \|), \quad \varepsilon \in \Omega, \quad i, j = 1, 2, ..., N, \quad (2) \]

where \( \Theta(\cdot) \) is the Heaviside function; \( \varepsilon \) is the size of a neighborhood for \( \mathbf{z}_i \); RS detection at the instant of time, and \( \Omega \) 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

\[ TRP_{ij}^* = \Theta(\varepsilon - \| \mathbf{z}_i - \mathbf{z}_j \|), \quad i \neq j, R_{ij}^* = 0. \quad (3) \]

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

\[ M_i(\varepsilon) = \frac{1}{i + 1} \sum_{i=0}^{i-1} TRP_{ij}^*. \quad (4) \]

A measure (4) makes it possible to estimate RS for each current \( i \) time instant based on (3) and taking into account \( \varepsilon \) size of the neighborhood of recurrent states. The measure depends on \( \varepsilon \) 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 operational monitoring of the state of the gas environment in the premises at a facility using measure (4) for increments of the states 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 \( \Delta t \) discrete time instants with \( \Delta t = 0.1 \) 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, \( \mathbf{z}_i \) 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 $\varepsilon=0.01$.

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...
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 emergency 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.

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