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DEVELOPMENT OF THE METHOD OF OPERATIONAL FORECASTING OF FIRE IN THE PREMISES OF OBJECTS UNDER REAL CONDITIONS

A method for operational forecasting of fires is proposed that enables the sequential implementation of five procedures. The method development is necessary to predict early fires in premises in order to take measures to prevent them from escalating into an uncontrolled combustion phase – a fire. As a result of research, it was found that a short-term forecast of the recurrence of increments of the air conditions by one step, based on the current measure of recurrence, is an effective indicator of early fires in premises. At the same time, it was found that before the moment of ignition of the material, the state of the air environment is characterized by dynamic stability, which is described by an irregular and time-dependent random change in the recurrence of the states of the vector of current increments of the state of the air environment. The values of the indicated levels of recurrence of the state increments are determined by the probability levels of 0.67 and 0.1, respectively. The probability of recurrence of state increments of 0.67 is characteristic of a larger number of measured states. When the material is ignited, the dynamics of the probability of recurrence of state increments change abruptly. There is a transition from two to one level of recurrence, close to zero probability – the loss of dynamic stability (in the region of count 250). Further dynamics are characterized by the appearance of separate random recurrent increments corresponding to the instability of the air environment in the premises. In the course of the experiment, it was found that the accuracy of predicting a fire by the proposed method ranges from 4.48 % to 12.79 %, which generally indicates its efficiency. The obtained data prove useful in the development of new systems that early warn of fire in premises, as well as in the modernization of existing systems and means of fire protection of premises

Keywords: fire forecasting, indoor ignition, measure of recurrence, increment of states, air environment

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1. Introduction

There are more than 250 countries in the world with 7.2 billion people. About 7–8 million fires occur annually, killing about 90 thousand people [1]. At the same time, it is known that a fire occurs only in the case of the presence of combustible material, an oxidizer, and conditions for its ignition [2]. The most dangerous are fires in ecosystems [3], at large production sites [4, 5], and critical infrastructure facilities [6]. However, fires in premises (FPs) occur most frequently. Such extreme events pose a significant threat to human life and health [7], the integrity and stability of the objects themselves [8], and also upset the balance in the natural environment [9]. Large-scale fires cause acid precipitation and subsequent pollution of aquifers [10]. In 2019, fire departments responded to a U.S. fire every 24 seconds on average, with respect to the National Fire Protection Association. At the same time, a message about an indoor fire was received every 93 seconds, death due to FP occurred every 3 hours 10 minutes, and injuries occurred every 43 minutes. FPs in 2019 caused property damage of USD 12.3 billion, which is 10.8 % more compared to 2018 [11]. On the whole, this data indicates the insufficient effectiveness of the known approaches to the prevention and prediction of FP, based mainly on the physical phenomenon of heat and mass transfer under appropriate conditions. At the same time, the conditions are mainly limited by the type of fire load and the structural and planning features of the premises. It determines the relevance of the development of methods for operational forecasting of FP, taking into account the real conditions in the premises of objects.

2. Literature review and problem statement

Paper [12] reports the results of research of modern methods of predicting a fire in premises (FP). It was shown that the methods are based on the calculation and mathematical modeling of the main hazardous aspects of FP. At the same time, the issues related to the operational forecasting of FP in real conditions were not resolved. This is explained by the fact that these methods make it possible to describe and calculate the deterministic change in the parameters of the state of the environment and enclosing structures in a room in time in general terms [13]. Due to the variety of premises and fire load, the operational forecast of FP in real conditions based on known methods is difficult to implement, since real conditions are characterized by rather complex individual dynamics of the current states of the indoor air environment (IAE). IAE at FP is an individual complex dynamical system, which is characterized by the properties of dissipative structures, the nonlinearity of states, and self-organization [14]. In such a system, the known methods do not allow one to identify complex relationships between elements, since they are based on the principles of linearity, which are usually not fulfilled in real conditions. This leads to an erroneous assessment of the real dynamics of the state of the IAE, which does not make it possible to promptly predict FP [15]. At the same time, the nature of the current dynamics of the state of the IAE is of paramount importance for predicting the FP in order to exclude the injury and death of the maintenance personnel, as well as the destruction of technological equipment and units in the premises of the objects [16]. Overcoming such difficulties can be carried out on the basis of using, for instance, methods of nonlinear dynamics [17]. Quantitative methods for evaluating the nonlinear dynamics of systems in the presence of noise and non-stationary conditions are studied in [17, 18]. In particular, the application of methods for analyzing time series in geophysics from the standpoint of the theory of dynamical systems and fractal sets is considered in [19]. However, methods of operational forecasting of hazardous conditions associated with FP in real conditions are not considered in [17–19]. An experimental study of the process of FP occurrence was carried out in [20]. The effect of thermal radiation on the rate of heat release for typical combustible materials is studied in [21]. The study of the combustion modes of various combustible materials under external thermal action on the basis of experimental data was carried out in [22]. Paper [23] reports a study of the rate of heat release during FP. It is noted that the dynamics of the state of IAE at the initial stage of the FP are complex and non-stationary. Paper [24] addresses improving the efficiency of known methods for detecting FP. At the same time, new methods, for example [25], capable of promptly predicting FP based on the current state of the IAE, are not considered. In [26], self-tuning methods for detecting fires are considered. In this case, the proposed methods are based only on the averaged values of the states of individual IAE parameters. The current dynamics of the IAE parameters at FP are not taken into account and are not analyzed. Due to the complexity of the dynamics of the state of the air environment in the room, the research results presented in [27] are limited only to the analysis of the dynamics of the adaptive threshold and the probability of detecting fires. The use of time autocorrelations and pairwise correlations to assess the dynamics of the main parameters of the IAE state during test fires in a model chamber was performed in [28]. It was noted that for detecting fires, the current indicators of the IAE state parameters are more important, rather than their averaged values. In [29], methods are considered that are suitable for identifying hazardous parameters of the state of the IAE during FP. However, these methods are valid only in the stationary approximation and only allow one to reveal the averaged energy indicators of the state parameters of the IAE. At the same time, the methods do not take into account the peculiarities of the time-frequency interaction of the parameters of the state of the gaseous environment and do not allow the operational prediction of FP. Methods of temporal and frequency detection of hazardous states of IAE during FP are considered in [30]. It is noted that the issue of temporal-frequency detection of hazardous states of the IAE during FP remains not fully resolved. The known methods turn out to be difficult to implement and have little use for the prompt detection of fires and forecasting FP. A method that takes into account the unsteady nature of state parameters of the IAE during ignition is studied in [31]. However, this method is based on the application of a Fourier transform to stationary fragments of the observed nonstationary dynamics of states. In [31], the IAE in the form of a complex dynamical system with FP is not considered, not investigated, and the dynamics of states are not predicted. A study of the dynamics of combustion rate of various materials in closed and ventilated premises is carried out in [32]. However, in the cited paper, there is no data on the features of the dynamics of IAE states while FP. Paper [33] reports a study into the dynamics of increments of individual hazardous parameters of the state of the IAE. It is noted that the dynamics of increments of the parameters of the state of IAE can be considered as an effective indicator of identifying the initial fires and predicting the FP. However, the research results are limited to the analysis of traditional statistical indicators of increments. Methods of operational FP forecast are not considered in this case. It is noted in [28–33] that the ignition of materials is a source of violation of the initial dynamic equilibrium state of the IAE. The dynamics of IAE states during ignition have a complex nonlinear and unsteady character. An attempt to identify these features of the IAE by methods of temporal-frequency identification of nonlinear dynamic systems is considered in [34, 35]. The application of the method of a short-term Fourier transform in this case is considered in [36]. However, these methods [34–36] turn out to be rather complicated to implement and cannot be considered for operational FP forecasting. In the cited papers, it is noted that the dynamics of states and increments of states of the IAE considered in the multidimensional phase space are important for identifying the FP. The application of the temporal-frequency method to the study of the peculiarities of the dynamics of the state of the IAE during ignition is considered in [37]. It is noted that the method turns out to be rather difficult to implement and has insufficient efficiency and parametric uncertainty. What is more, this method, being an energetic one, in fact, does not allow one to estimate the dynamics of IAE states in the phase space.

Thus, it was established that the dynamics of the states of an IAE at FP have a complex and nonlinear character that depends on specific conditions. In order to promptly detect FP, it is proposed to use various temporal-frequency methods. However, such methods are rather complicated to implement, have limited sensitivity, efficiency, and scope. Therefore, their application for operational FP forecasting turns out to be problematic. Methods of nonlinear dynamics should be considered more suitable for the operational prediction of FP based on the current dynamics of IAE states [38]. These methods should be based on the assessment of the dynamics of the recurrence of increments of the state of the IAE during FP. Therefore, an important and unsolved part of the issue under consideration is the development of an operational method for predicting the FP based on the current recurrence of increments of the IAE state in real conditions.

3. The aim and objectives of the study

The aim of this work is to develop a method for the operational forecasting of a fire based on the use of the current measure of recurrence of increments in the state of the air environment in the premises of objects.

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

– to substantiate the method of operational forecasting of a fire based on the use of recurrence plots and measures of recurrence for increments of the state of the air environment in a room, as well as predicting the recurrence of state increments in real time;

– to check the performance of the proposed method using the example of ignition of test material in the form of cellulose in a laboratory chamber simulating a leaky room of an object.

4. The study materials and methods

The method is based on the results of the system analysis of the FP occurrence, performed in [15]. It is known that when FP occurs, the state of IAE is determined by a combination of various hazardous factors [12]. This set of factors will determine the corresponding vector characterizing the state of the IAE. In this case, the number of hazardous factors in the aggregate can be arbitrary. Typically, the main hazards include temperature, smoke density, and carbon monoxide concentration in IAE. Therefore, when justifying the proposed method, we will restrict ourselves to considering the indicated hazardous factors of IAE. We will assume that the current IAE state vector is characterized by the indicated components at a fixed time. An increase in the number of factors under consideration will only affect the dimension of the current IAE state vector. Let the IAE at FP represent a certain complex dynamic system, the state of which is determined by the peculiarities of the ignition source, premises, and various disturbances [39]. Moreover, these features are usually unknown in real conditions and can change over time. It is not possible to assess the state of such a system taking into account all the features. However, its condition can be assessed on the basis of the real-time measurement information of IAE hazardous factors. For this purpose, various types of sensors can be used, for instance, used in existing fire protection systems for premises.

The verification of the method of operational prediction of FP was carried out on the basis of experimental data obtained during the ignition of cellulose in a modeling chamber [33]. In the course of the experiment, the current values of hazardous factors in the air environment of the chamber (AEC) were measured, determined by the density of smoke, temperature, and concentration of CO. Hazardous factors were measured at discrete times i=0, 1, 2, ..., 400. This means that for the i-th sample the value of the vector (1) of the state of the AEC was determined by the value x_i. The ignition of cellulose in the chamber was carried out in the region of i=200 counts. The sensors TGS2442 (Japan), DS18B20 (Germany), and MQ-2 (China) were used as meters for smoke density, temperature, and concentration of CO AEC, respectively.

5. Substantiation of the method of operational forecasting of fire in the premises

The proposed method involves performing a number of procedures. In a general case [40], the measurement information for an arbitrary discrete time moment i can be represented by an m-dimensional vector of the state of hazardous factors.

$$x_i = d_i + \Delta_i, \quad i = 0,1,2,...,N_S - 1, \tag{1}$$

where d_i is the vector of unknown current states of the IAE caused by the ignition source; Δ_i is the vector of unknown current disturbances of the state of the IAE; N_s is the size of the measurement sample of the specified state vector.

In this regard, the first procedure of the method includes obtaining measurement information about the current state vector (1) of the IAE.

The second procedure of the method is related to the determination of the current increments of the IAE state vector in accordance with the following expression

$$z_i = x_i - x_{i-1}. \tag{2}$$

The third procedure of the method is to study the dynamics of the states of the IAE when the FP appears in the form of a complex system. For this purpose, it is proposed to use the method of recurrent plots (RP) [38] but apply it to the current increments (2). The RP method allows one to visually investigate the features of complex dynamic systems of any nature. In the case under consideration, the application of the RP method to (2) makes it possible to map the features of the dynamics of the increments of the state of the VSP with SP in the m-dimensional space onto a two-dimensional binary matrix of size $N_s \times N_s$. In this case, the unit element of this matrix for arbitrary times *i* and *j* will reflect the configuration of the distribution of recurrent states (RS) in the dynamics of increments of the state of the VSP during ignition. However, the classic RP method is not operational. Therefore, for the efficiency of the RP method, it is necessary to use its modification [15], defined as:

$$TRP_{i,j}^{m,\varepsilon}=if\left(i\neq j\bigcap j\leq i,\Theta\left(\varepsilon-\left|z_i-z_j\right|\right),0\right), \qquad (3)$$

where Θ () is the Heaviside function; ε is the assigned size of the neighborhood for PC (2) at arbitrary times *i* and *j*.

The fourth procedure of the method is to use the RP method for quantitative analysis of MS [41]. Methods for quantifying MS are based on appropriate measures. PC measures allow displaying special conditions in the systems under study. In the case under consideration, for quantitative analysis of the complexity of the PC dynamics for the increment vector (2), method (3) is used. In [42], PC measures for the concentration of atmospheric air pollution based on the use of states are proposed. However, these measures cannot be used to quickly identify the features of the state of IAE in the event of FP. The main limitation of the known PC measures is the lack of promptness in identifying the features in the dynamics of the IAE states during ignitions. Therefore, by analogy with [41], it is proposed to use the PC measure determined on the basis of (3) for the increments of the IAE states during ignition. This PC measure for increments (2) of the VSP states during ignition will be determined [15] in the form:

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

With the help of measure (4), it is possible to reveal the features of the dynamics of the PC of increments (2) of the states of IAE in real time. The PC measure (4) numerically characterizes the dynamics of the estimation of the PC probability of increments of the IAE states at FP in real time. Measure (4) makes it possible to study the features of the transition from dynamically stable states to unstable states of an IAE during FP. This is explained by the fact that state increments (2) are more sensitive to indoor fires. In [43, 44] it is noted that the increments of the IAE states are more sensitive to early ignitions in rooms. In addition, it is indicated that, on the basis of measure (4), it is possible to identify the moments of loss of dynamic stability of the state increments (PC) of the IAE during fires and to predict the FP.

The fifth procedure of the proposed method includes the application of methods for predicting the PC measure (4) based on its current assessments in real time. Currently, over 200 forecasting methods are known. Moreover, most of these methods turn out to be difficult to implement and do not always ensure the efficiency and accuracy of the forecast. These methods are mainly designed to take into account the trend and seasonality in data that are not typical for the considered increments (2). Therefore, when choosing a method for predicting FP in rooms based on the PC measure (4), first of all, the efficiency of the forecast method (the method of short-term forecast) and the simplicity of the algorithm for its implementation were taken into account. These conditions are satisfied by the simplest forecasting method based on the algorithm of simple exponential smoothing. This method makes it possible to carry out a short-term forecast by one step according to the current measure PC (4) of the increments of the vector of IAE states during fires. Despite the simpler and more accessible mathematical apparatus, forecasting using exponential smoothing models often gives a result comparable to the result obtained using the ARIMA model.

Forecasting based on simple exponential smoothing, in this case, will be defined as:

$$Y_{i+1}=\alpha M_2(i,\varepsilon)+(1-\alpha)Y_i, \qquad (5)$$

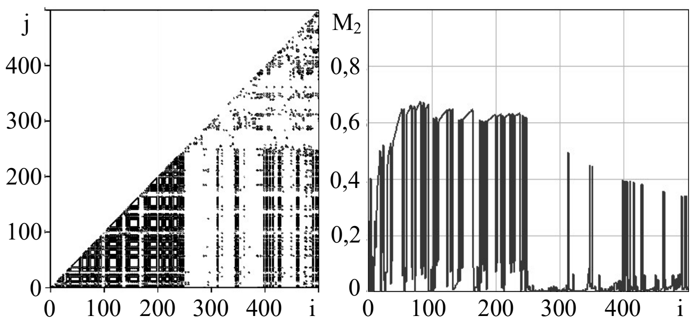
where Y_{i+1} is the RS forecast for the increment vector at the moment *i*+1; α is the fixed parameter, the value of which is selected from the condition $0\leq\alpha\leq1$; Y_i is the PC forecast for the increment vector at time *i*.

In method (5), the parameter α determines the dependence of the forecast on the "older" data, and the influence of the data on the forecast decreases exponentially with the "age" of the data. If forecasting is performed using an exponential smoothing model, usually predictions are made on a certain test set for different values of the parameter α and it is tracked at which value of α the prediction accuracy is higher. This value of α is then used in future predictions. It can be seen that with a value of α=1, the exponential model (5) tends to the simplest "naive" model, and with a value of α=0, the predicted value becomes equal to the previous forecast.

Thus, the proposed method of operational FP forecasting in real conditions is implemented based on the implementation of the five procedures described above. At the same time, the operational forecasting of the FP by detecting early fires based on the PC of the increments of the IAE states makes it possible to take timely measures to prevent them in order to eliminate the threat to human life, equipment failure, and destruction of the facility's premises structures.

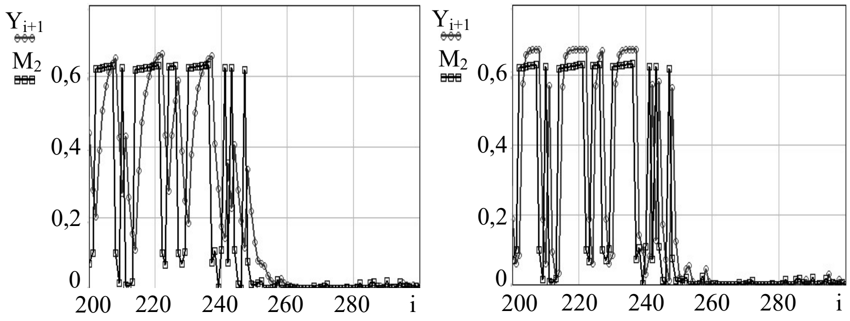
6. Checking the efficiency of the method using the example of ignition of cellulose in a model chamber

According to the proposed method, the current measurements (1) were used to determine the vector of current increments (2) of the AEC. Fig. 1, *a* shows RP (3) for the increments of the state of the AEC for *i*=0, 1, 2, ..., 500 and *j*=0, 1, 2, ..., 500 when the cellulose is ignited in the chamber in the case of the value ε=0.01. An illustration of the dynamics of the measure PC (4) (estimates of the probability PC) based on expression (3) for the increments of the state of the gaseous medium in the case ε=0.01 is shown in Fig. 1, *b*. Fig. 2 shows the corresponding dynamics of the PC forecast by one step in accordance with expression (5) and the current PC measure (4) for two values of the parameter α=0.4 and α=0.83, respectively. Illustrations of the dynamics in Fig. 2 correspond to the measurement interval from 200 to 300 counts.



a *b*

Fig. 1. RP for the increments of the state of the air environment and the PC measure during the ignition of cellulose in the model chamber: *a* – RP (2); *b* – measure PC (4)



a *b*

Fig. 2. The dynamics of the RS forecast of the increments of state (5) of the air environment in the model chamber during the ignition of cellulose: *a* – α=0.4; *b* – α=0.83

In the process of testing the method, the forecasting accuracy was assessed. The most common estimate of prediction accuracy is the Mean Squared Error (MSE) over an interval. Sometimes, as a disadvantage of MSE estimates, it is indicated that it is oversensitive to rare single errors of large magnitude. Alternatively, it is suggested using the Mean Absolute Error (MAE). Here, the operation of squaring the error value is replaced by the use of its absolute value. It is assumed that more robust assessments can be obtained using MAE. Both estimates are well suited for determining the prediction accuracy, for example, of the same PC sequence for different α parameters. So, for the case in Fig. 2 with a value of α=0.83, MSE accuracy=5.02 %, and MAE accuracy=11.28 %. In this case, in the case of the parameter α=0.4, the values of MSE and MAE are equal to 4.48 % and 12.79 %, respectively.

The dependences shown in Fig. 1, 2 were obtained taking into account the real measurement errors of the components of the state vector of the AEC by the sensors. Therefore, taking into account the methodological error, assuming that real modern fire detectors of various types are constructed on the basis of the sensors used, it can be assumed that the data obtained satisfy the corresponding degree of reliability.

7. Discussion of the results of checking the fire prediction method

The results obtained are explained by the complex dynamics of the increments of the state of the main hazardous factors of the IAE, considered in the form of a non-stationary system. At the same time, to assess the indicated dynamics, it is proposed to use a modified RP method capable of visually identifying the features of the dynamics of IAE increments. In this way, for example, from the analysis of RP in Fig. 1, *a*, it turns out that the dynamics of the increments in the state of the AEC during the ignition of cellulose turn out to be really unequal. At the same time, until the moment of ignition, the dynamics of the increments of the state of the AEC are characterized by a regime of dynamic stability, which is determined by an abrupt change of two states during rather short time intervals. This mode corresponds to normal conditions in the absence of ignitions and FP. White areas on RP in this mode indicate the absence of recurrence of the increments of the state of the AEC. These areas are characteristic of the moments of loss of recurrence (stability) of the increments of the state of the AEC and correspond to the possible appearance of a hazard associated with the ignition of the material in the chamber. Further dynamics of the increments of the state of the AEC are chaotic due to the instability of its state. Moreover, in Fig. 1, *a* the boundary of the loss of dynamic stability is clearly fixed (white area, in the region of 250 counts). Therefore, it can be argued that the above RP graph as a whole allows you to visually display the appearance of a hazard in the form of material ignition. A feature of the method is the triangular view of the modified RPs in Fig. 1, *a*. The RP data differs from the known data in that it allows displaying the recurrence of the IAE state increments in real-time measurements. Therefore, the use of the modified RP method, in contrast to the known methods, makes it possible to calculate the measure of PC (4) (Fig. 1, *b*) in real time. This allows it to be used for the early detection of material fires and to prevent the outgrowth of fires in the FP. Another feature of the proposed method is the use of an assessment of the current PC measure (4) for a short-term forecast of early ignition of materials and prevention of FP, provided that ignitions are extinguished in a timely manner using available means. The experimental dynamics of the proposed short-term forecast of ignition (5), implemented on the basis of the method of exponential smoothing of the current PC measure (4) for various values of the smoothing parameter α is shown in Fig. 2. The obtained result testifies to the possibility of operational prediction of the FP of objects based on the proposed method.

Thus, the data shown in Fig. 1, 2 indicate, in general, the features of the performance of the proposed method of operational forecasting of FP under real conditions.

The limitations of this study include the fact that the results of testing the proposed method were obtained using the example of experimental data on the ignition of cellulose in a model chamber. In addition, the effectiveness of the proposed method will depend on the sensitivity and distance of the corresponding sensor from a possible source of ignition in the room. Therefore, in the practical implementation of the method, it is advisable to place the measuring sensors of hazardous factors of the air environment of the FP in the zones with the highest probability of ignition. Typically, such areas in the premises of objects are known in advance. Traditionally, the ceiling area of the room is chosen as such a zone. Possible ways of further development of the study can be considered the expansion of the experimental verification of the efficiency of the method in the case of various types of premises of objects and fire loads in them. In the course of the experimental verification, it is necessary to assess the limits of applicability and limitations of the proposed method, the conditions for the stability of the results, as well as other indicators and parameters that affect the scope of the practical application of the method for the operational prediction of FP in various rooms of objects.

8. Conclusions

1. The method of operational fire forecasting has been substantiated, which assumes the sequential implementation of five procedures. The first procedure involves obtaining measurement information about the current vector of the state of hazardous factors of the indoor air environment. The second procedure is related to the determination of the current increments of the air state vector. The third procedure is based on the study of the dynamics of the state of the air environment in premises based on the use of the RP method for the current state increments. The fourth procedure involves quantitative analysis of PC based on the RP method for air state increments. The fifth procedure is based on the application of methods for predicting the PC measure based on its current estimates in real time. For operational forecasting of a fire in the premises of objects, it is proposed to use the simplest forecasting method based on exponential smoothing. This method makes it possible to carry out a short-term forecast of the PC by one step based on the current PC measure of the increments of the vector of the states of the air during the ignition of materials in the premises of objects in real conditions.

2. The operability of the proposed method of operational forecasting of a fire in the premises of objects has been tested on the example of the state of the air environment in a model chamber when cellulose is ignited. It is established that the state of the air environment in the chamber is characterized by dynamic stability until the moment of ignition of the test material. This state is determined by an irregular random change in time in the recurrence of the vector of current increments of the state of hazardous factors of the air environment. The presence of two levels of probability of recurrence of such increments of states is noted. For the conditions of the experiment, it was determined that the indicated levels of recurrence of state increments correspond, on average, to probabilities of 0.67 and 0.1, respectively. In this case, the probability of recurrence of state increments, equal to 0.67, is characteristic of a larger number of measurements of the vector of the state of the air in the chamber. At the moment of ignition of the test material, the dynamics of the probability of recurrence of state increments change abruptly. A transition to one level of recurrence of increments is noted, characterized by a probability close to zero – there is a loss of dynamic stability of the states of the gaseous medium, which took place before the ignition of the material. According to the results obtained, the loss of dynamic stability of the state in the experiment occurs in the region of 250 counts, which corresponds to the real moment of ignition of the test material. After lighting up, the dynamics of the recurrence of state increments is characterized by separate recurrent random points on RP. Such a state of the air environment corresponds to the instability of the increments of the states of the air environment and its chaotic dynamics. The accuracy of predicting a fire (instability of increments in the states of the air environment), according to various estimates, ranges from 4.48 % to 12.79 %. The results obtained indicate, in general, the operability of the proposed method of operational forecasting of a fire in the premises of objects under real conditions.

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