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DEVELOPMENT OF A METHOD FOR ASSESSING THE RELIABILITY OF FIRE DETECTION IN PREMISES

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The object of this study is the detection of fires in the premises. The problem that was solved is the development of tools to assess the reliability of detection of fires in the premises based on the recurrence of the vector of increases in dangerous parameters of the gas environment. The method includes the sequential implementation of five procedures related to the formation of the vector of current increases in dangerous parameters, determining the recurrence of the current vector and evaluating the empirical distribution function relative to the calculated current recurrence of the state vector. Features and distinctive attributes of the developed method are the use of empirical cumulative distribution function in relation to the current recurrence of the state of hazardous parameters of the gas environment in the premises during fires. This makes it possible to solve the task of developing tools for the numerical determining of the trust limit for the predefined level of significance (reliability) and the likelihood of detecting fires in the premises in real time. The scope and conditions for the practical use of the obtained results are the modern and promising means and fire protection systems of various types of premises in buildings and structures. The proposed method was tested on the example of igniting test materials in the laboratory chamber. It is established that for materials with a high combustion rate (alcohol and cellulose) with a probability of 0.95, there is a sharp decrease in the value of the empirical function assessment to zero values. For timber, the value of this estimate is 0.15, and for textiles, the minimum value of the estimate is 0.31. It is established that the boundaries of the confidence interval with the level of significance covering the obtained estimates are determined by the value of ±0.086. In general, the results of the test indicate the operability of the proposed method for determining the reliability of detection of fires in the premises on the basis of the current degree of recurrence of increases in dangerous parameters of the gas environment

Keywords: fire detection, empirical distribution function, confidence interval, probability of fire, recurrence

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1. Introduction

Every year in the world there are about 8 million fires. As a result of fires, about 90 thousand people die annually [1]. Fires can occur everywhere. Usually, fires occur in ecosystems [2], in production [3, 4], and at various critical infrastructure facilities [5]. At the same time, most fires occur in the premises of objects [6] for technical and residential purposes. The particular danger of indoor fires (IF) is associated with a significant threat to human life [7] and causing enormous damage to the objects themselves [8, 9], as well as to the environment [10]. Fires can provoke acid precipitation [11] and pollution of aquifers [12]. IF during 2019 alone in the U.S. amounted to more than USD 10 billion in damage [13]. Due to the noted danger to humans and the environment, a special place is given to extinguishing fires [14–16]. At the same time, it is known that the most effective is considered to be the prevention of fires. Prevention of fires is associated with the identification of ignition and their prompt extinguishing, preventing the occurrence of fire. In this regard, the reliability of the detection of fires is currently one of the urgent problems.

2. Literature review and problem statement

The study into the dynamics of hazardous parameters of the state of the gas environment of premises (GEP) in the case of fire is reported in [17]. It notes that the dynamics of increments of hazardous parameters of the GEP state can be considered an effective sign for detecting fires in the premises. At the same time, the results are limited to the study of only traditional known statistics. Non-traditional statistics, as well as on their basis, technologies for identifying and determining the reliability of fires in [17] are not considered. Paper [18] notes that in general, the dynamics of hazardous parameters of the GEP in a fire are individual, previously unknown, and non-stationary. It depends in a complex way on many previously unknown factors accompanying the process of ignition and the occurrence of fire. At the same time, the real dynamics of the dangerous parameters of GEP turn out to be similar to the dynamics of some nonlinear dissipative system with elements of self-organization [18]. The use of known linear technologies, in this case, will lead to erroneous detection of fires [19]. At the same time, paper [20] notes that the nature of the dynamics of hazardous parameters of the GEP is of particular importance for the reliable detection of fires. However, methods for identifying fires and determining the reliability of their assessment are not considered in [18–20]. An attempt to overcome the uncertainty and non-stationarity of the dynamics of hazardous parameters of GEP in order to reliably identify fires based on the use of self-tuning technology is considered in [21]. However, self-adjustment is carried out in relation to the average values of the hazardous parameters of GEP. The results of the test of self-adjustment technology in real conditions are presented in [22].

Due to the complexity and uncertainty of the dynamics of the hazardous parameters of GEP, the results of the studies in [23] are limited to the analysis of the dynamics of the self-adjustment of the threshold, as well as the assessment of the probability of detecting fires. At the same time, the reliability of the assessment of the detection of fires is not considered. To take into consideration the complex and uncertain dynamics of hazardous parameters of GEP in real conditions, nonlinear dynamics methods can also be used [24]. Thus, in [25], the correlation dimension of the vector of GEP states during the ignition of various materials is analyzed. Paper [26] investigates dynamic correlations for the main hazardous parameters of GEP during the ignition of test materials in the model chamber. It is shown that for the detection of fires, current statistics of hazardous parameters of GEP are preferable. At the same time, the reliability of the assessment of fires is not investigated. Methods for determining the reliability of the assessment of fires are also not proposed. Work [27] discusses procedures that can in principle be used to identify hazardous GEP parameters in the event of IF. However, these procedures are suitable only in a stationary approximation and make it possible to identify only the average energy characteristics of hazardous parameters. This does not take into consideration the peculiarities of localization in time of dangerous parameters and for this reason, have limited use for detecting fires. Technologies for the temporary localization of the values of hazardous parameters of GEP are considered in [28]. However, determining the reliability of the assessment of the detection of fires in the room remained unexplored. The theory and technology of semi-adaptive calculation of recurrence plots based on process measurement data under uncertainty conditions are described in [29]. However, the method for determining the reliability of detecting fires from recurrent plots of hazard parameters of GEP is not considered. The development of a method for operational forecasting IF at objects in real conditions is presented in [30]. In [31], based on the recurrent state of GEP, a technology for short-term fire forecasting is proposed. At the same time, in [30, 31], the proposed forecasting technologies do not affect the methods for determining the reliability of detecting fires in real conditions.

Thus, it follows that the dynamics of hazardous parameters of GEP during the ignition of materials have a rather complex and nonlinear character, depending on many factors that cannot be taken into consideration in advance. Various methods and technologies are proposed for the early detection of fires. However, most of them have implementation difficulties and have limited sensitivity and efficiency in relation to fires. Methods of nonlinear dynamics of systems should be considered more constructive for identifying and forecasting fires by the dynamics of hazardous parameters of GEP [32]. In this case, these methods should be based on the dynamics of the recurrent increments for the hazard parameters of GEP based on the determined recurrence plots. However, there are no studies that address the reliability of detecting fires based on these methods. In this regard, an important and unresolved part of the problem of reliable detection of indoor fires is the lack of tools to assess the reliability of fire detection based on current recurrence.

3. The aim and objectives of the study

The aim of this work is to develop a method for assessing the reliability of detecting fires in the premises based on the use of the current measure of recurrent increments of hazardous parameters of the gas environment. This method will make it possible in practice to detect fires in rooms with predefined reliability and warn about the occurrence of a fire.

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

– to theoretically substantiate a method for assessing the reliability of detecting fires in premises based on the current measure of the recurrent vector of increments of hazardous parameters of the gaseous medium;

– to perform a check of the proposed method to assess the reliability of the detection of fires on the example of fires of test combustible materials in a laboratory chamber simulating a leaky room.

4. The study materials and methods

The materials of our study represented the results of measuring the hazardous parameters of the gas environment in the laboratory chamber during the ignition of test materials in the form of alcohol, wood, cellulose, and textiles [17]. The most common and dangerous parameters for humans [33] were measured: smoke density, average volumetric temperature, and carbon monoxide concentration. Measurements were performed at discrete moments of time corresponding to counts i=0, 1, 2, ..., 400 with an interval of 0.1 seconds. In this case, the measured hazardous parameters at discrete moments were considered as corresponding components of the studied vector x_i of the state of the gaseous medium. The TGS2442 (Japan), DS18B20 (Germany), and MQ-2 (China) sensors were used as hazard measurement sensors, measuring smoke density, mean volume temperature, and carbon monoxide concentration, respectively. The ignition of the test materials in the chamber was carried out in the region of count i=230, which corresponded to about second 23 from the start of the measurement. In general, the number and variety of hazardous parameters in the state vector of the gaseous medium may be arbitrary. At the same time, an increase in the number and type of hazardous parameters under consideration in the vector of the state of the gas medium will affect only the dimensionality of the vector itself. Research methods are based on the analysis of the state of the gaseous medium during the ignition of test materials. At the same time, the gaseous medium is considered in the form of some complex dynamic system. The state of this system depends on many unknown parameters, for example, the characteristics of the fire site, the characteristics of the room, and various perturbations [34–36]. Due to the complexity of the system under consideration, nonlinear dynamics methods are used to detect fires in the form of a modified method for calculating recurrence plots for the current values of the vector of increments of the state of the gaseous medium. To assess the reliability of detecting fires in the premises based on the use of the current measure of the recurrence of the vector of increments of hazardous parameters of the gas environment, the method of the sample distribution function was used [37, 38].

5. Results of development of a method for assessing the reliability of the detection of fires in the premises

5. 1. Theoretical substantiation of the method for assessing the reliability of detecting fires in the premises

The proposed method involves performing a number of procedures. The first procedure involves the measurement of hazardous parameters of GEP. This procedure is implemented with the help of measuring sensors. According to the measurement data, the current values of the state vector x_i of GEP are formed, where i=0, 1, 2, ..., N_s–1. Here, N_s is determined by the maximum number of discrete measurements performed by each of the sensors. The second procedure of the method implies the formation of the current increments of the GEP state vector in accordance with the expression:

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

The third procedure includes estimating the dynamics of the recurrence of the vector of increments of the states of GEP (1) in accordance with the modified method of recurrent plots [39] in accordance with the expression:

$$TRP_{i,j}^{m,\varepsilon} = if\left(i \neq j \bigcap j \leq i, \Theta\left(\varepsilon - \left|z_i - z_j\right|\right), 0\right), \tag{2}$$

where $\Theta()$ is the Heaviside function; ε is the given size of the neighborhood of recurrence for vectors (1) considered at arbitrary time points i and j.

The fourth procedure is to form, based on (2), an estimate of the current measure of recurrent increments of the GEP state increments, defined as [39]:

$$M_2(i,\varepsilon) = \frac{1}{i+1}\sum_{k=0}^{i} TRP_{i,k}^{m,\varepsilon}. \tag{3}$$

Measure (3) is an estimate of the dynamics of the probability of recurrence of the vector of increments of the states of the gas medium during fires in the premises for arbitrary values ε and i. At the same time, the current value of measure (3) is a sign of the transition from a dynamically stable state of the gas medium to its unstable state [39]. Paper [39] also notes that a given point in time indicates the moment of the beginning of the fire in the room.

The fifth procedure is to form the current empirical distribution function $F_M(i, y, \varepsilon)$ for the current measure (3). This empirical distribution function is equivalent to the survival function [40]. To calculate this function, a finite sample the size of $M \ll N_s$ is used. Therefore, this empirical estimate of the distribution will be determined by the expression

$$F_M(i,y,\varepsilon) = \text{if}\left\{\begin{matrix} i \leq M, \dfrac{1}{i+1}\sum\limits_{k=0}^{i}\Theta\left(y - 1 + M_2(k,\varepsilon)\right), \\ \dfrac{1}{M}\sum\limits_{k=i}^{i-M}\Theta\left(y - 1 + M_2(k,\varepsilon)\right) \end{matrix}\right\}. \tag{4}$$

Estimate (4) will characterize the probability that measure (3) exceeds the given level y. At the same time, following [41], the choice of the value of M will affect the boundaries of the confidence interval of assessment (4). Taking into consideration [42, 43], estimate (4) from a sample of a fixed size M makes it possible, for a given probability y of the detection of fires, to determine the boundaries of the confidence interval at an arbitrary level of significance (reliability) α at each time i.

Thus, the proposed method for assessing the reliability of detecting fires in arbitrary rooms based on the recurrent increment vector of hazardous parameters of the gas environment (1) to (4) includes the sequential implementation of the above five procedures.

5. 2. Verification of the proposed method for assessing the reliability of the detection of fires

Verification of the method was carried out on the example of igniting test combustible materials in the form of alcohol, cellulose, wood, and textiles in a laboratory chamber simulating a leaky room. Following [43], to estimate (4) at ε=0.01 in the case of significance (confidence) level α=0.95 and sample size M=50, the boundaries of the confidence area will be determined by the value $\gamma = \sqrt{\frac{-0.5\ln(\alpha/2)}{M}}$. With given values α and M, the value is $\gamma = \pm 0.61/\sqrt{50} = \pm 0.086$. This means that the theoretical value of the distribution function $F(i, y, \varepsilon)$ for the probability level y=0.95 is within the interval $Gn1(i) \le F(i, y, \varepsilon) \le Gv1(i)$, the corresponding boundaries of which are determined by $Gn1(i)=F_M(i, y, \varepsilon)-\gamma$ and $Gv1(i)=F_M(i, y, \varepsilon)+\gamma$. For our experimental verification of the method, the value of the level y in (4) was chosen equal to 0.95. This means that the decision to ignite materials in the room was made on the condition that measure (3), characterizing the probability of loss of stability of the GEP state, exceeded 0.95. As an illustration, Fig. 1 shows the dependences characterizing the dynamics of the empirical assessment (4) (the red curve) and the corresponding boundaries of the confidence interval (the blue curve corresponds to the lower boundary, and the green color corresponds to the upper boundary). The curves in Fig. 1, *a* correspond to the test material in the form of alcohol, and in Fig. 1, *b* – to the tested material in the form of cellulose. Similar dependences for wood and textiles are shown in Fig. 2.

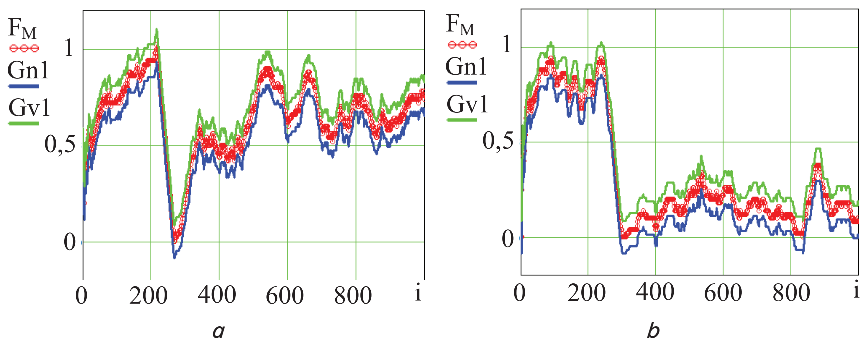

Fig. 1. Dynamics of empirical evaluation (4) and the corresponding boundaries of the confidence interval for various test materials: *a* — alcohol; *b* — cellulose

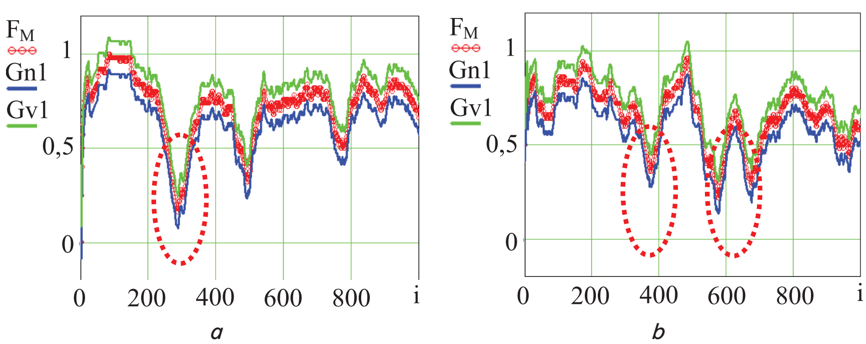

Fig. 2. Dynamics of empirical evaluation (4) and the corresponding boundaries of the confidence interval for various test materials: *a* — wood; *b* — textiles

The dependences in Fig. 1, 2 were derived taking into consideration the real measurement errors of the corresponding sensors of the components of the vector of the state of the hazardous parameters of the gas environment in the laboratory chamber when igniting test materials. Believing that the sensors used for hazardous parameters of the gas environment are part of modern fire detectors, we can consider the results obtained plausible.

6. Discussion of results of the method performance check

Our results are explained by the complex dynamics of the vector of increments of the state of the gaseous medium for the considered hazardous parameters during the ignition of test materials. In general, the dynamics of the empirical evaluation (4) and the corresponding boundaries of the confidence interval for the various test materials presented in Fig. 1, 2 indicate this. At the same time, estimates (4) for various test materials are individual. Comparing them, it can be concluded that for materials with a high rate of combustion (alcohol and cellulose), the dynamics of empirical evaluation (4) are characterized by the presence of a sharp change from values close to unity to zero values. This nature of the change in dynamics corresponds to the state of loss of dynamic stability of the state of the gas medium. These points in time correspond to the ignition of materials. The subsequent dynamics of the empirical evaluation (4) for alcohol and cellulose are of a different nature, due to the special combustion properties of these materials. It should be noted that the empirical estimate (4) determines the probability of an event associated with the excess of a given level y by the current probability estimate $1-M_2(i, \varepsilon)$. This means that when the stability of the gas medium is lost, the measure $M_2(i, \varepsilon)$ tends to zero while the probability estimate $1-M_2(i, \varepsilon)$ tends to unity. Often, such an event is called a survival event. In our case, the magnitude of the level y will determine the level of survival, and the survival event should be interpreted as an event of ignition of the material. Therefore, the value of the level y will determine the probability of ignition. The dependences that are shown in Fig. 1, 2 were obtained for a confidence level y of 0.95. In this regard, they characterize the corresponding dynamics of the probability of estimation (4) and its confidence limits for the probability of ignition of materials equal to 0.95. From the analysis of the curves in Fig. 2 it follows that for a given probability of wood and textile ignition of 0.95, the nature of the dynamics is generally different from that of alcohol and cellulose. At the same time, in the dynamics for wood, the moment of initial ignition is observed (highlighted in red) with the estimate (4) equal to 0.15. Subsequent dynamics are caused by asynchronous ignition of varying intensity. In contrast, in the dynamics for textiles (Fig. 2, *b*), there is a less pronounced onset of ignition (the first region of red color), characterized by an estimated value (4) equal to 0.31, followed by asynchronous ignition of varying intensity (the second region of red color). The boundaries of the interval covering the current unknown values of the estimate (4) for the given probability of ignition of 0.95, shown in Fig. 1, 2, are determined by the value of ±0.086 with a level of significance α=0.95. This means that the ignition of the corresponding combustible material with a probability of 0.95 is characterized by a confidence interval with boundaries of ±0.086 and a significance level of α=0.95. The data presented indicate the feasibility of the proposed method for assessing the reliability of detecting fires in the premises based on the current measure of recurrent increments of hazardous parameters of the gas environment. The limitations of this study include the verification of the method on the example of experimental data for the finite set of ignition materials. The conditions of the laboratory experiment performed differ from the real conditions of ignition in the premises.

7. Conclusions

1. A method has been developed to assess the reliability of detecting fires in the premises. The method is based on the assessment of the current measure of recurrence for the vector of increments of an arbitrary number of various hazardous parameters of the gas medium in the room and the calculation, on its basis, of the empirical cumulative distribution function, but for the corresponding survivability function. The implementation of the developed method includes the sequential execution of five procedures. The first procedure implies measuring the dangerous parameters of the gas environment in the room with the help of appropriate sensors and the formation of the current vector of the state of the gas environment. The second procedure comes down to the formation of the current increments of the vector of the state of the gas medium. The third procedure is associated with determining a modified assessment of the dynamics of the recurrence of the vector of increments of the states of the gaseous medium. The fourth procedure is the formation of an assessment of the current measure of the recurrence of the vector of increments of the states of the gaseous medium. The fifth procedure involves the formation of an empirical assessment of the distribution function for the current survival measure corresponding to the current measure of the recurrent measure of the vector of increments of the states of the gaseous medium. Sequential execution of these procedures of the method makes it possible to determine the trust boundaries taking into consideration the given level of significance for a given probability of detecting fires in real time.

2. The proposed method for assessing the reliability of detecting fires was checked on the example of fires of test combustible materials in a laboratory chamber simulating a leaky room. It was established that the dynamics of empirical evaluation and the corresponding confidence boundaries for various materials are complex and individual in nature. At the same time, for materials with a high rate of combustion (alcohol and cellulose) in the dynamics of the evaluation of the empirical function, there is a sharp decrease in the value of the estimate to zero values. It was found that the detection of the ignition of wood and textiles with a probability equal to 0.95 differs from that of alcohol and cellulose. At the same time, for wood, the moment of ignition is characterized by a minimum value of the empirical assessment equal to 0.15. In textile dynamics, the moment of ignition is characterized by a minimum value of the empirical assessment of 0.31. It was established that the boundaries of the confidence interval with a significance level of 0.95, which covers the assessment of the empirical distribution function for the probability of ignition of 0.95, are determined by the value of ±0.086. It is noted that the results of the check, in general, indicate the possibility of the proposed method to assess the reliability indicators for detecting fires in the premises based on the use of the current measure of recurrent increments of hazardous parameters of the gas environment.

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