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The object of this study is the dynamics of a characteristic sign of an increment in the state of the gaseous medium in the premises when a thermal source of fire appears. The subject of the study is the type of an empirical cumulative function of the distribution of dynamics of a characteristic sign of an increment in the state of the gaseous medium in the absence and appearance of a thermal source of fire in the premises. As a characteristic feature, the probability of non-recurrence of the increments of the vector of states of the gaseous medium was chosen. The results of the study make it possible to quickly identify thermal sources of fire under uncertain conditions. The methodology for studying the empirical cumulative function of the distribution of the dynamics of the probability of non-recurrence of the increments of the vector of the state of the gas medium has been substantiated. The technique includes the implementation of seven consecutive procedures and makes it possible to explore the specified function for arbitrary time intervals. The empirical cumulative distribution function for two fixed time intervals of equal duration before and after the appearance of test thermal sources of fire in the laboratory chamber was investigated. It was established that the features of the empirical cumulative functions of the distribution of the dynamics of the probability of non-recurrence of the increments of the vector of the state of the gas environment allow for early detection of fire. The main sign of detection is a decrease in the fixed values of the empirical cumulative distribution function. For test thermal sources, fixed values of the empirical cumulative distribution function are in the range of 0.15–0.44. These probabilities are determined by the different ignition rate of the test thermal sources. The research results indicate the possibility of using the identified features of empirical cumulative distribution functions of the dynamics of the probability of non-recurrence of increments of the vector of the state of the gas environment for the early detection of fires

Keywords: gas environment, dynamics of increments of states, thermal sources of fire, empirical cumulative distribution function

EMPIRICAL CUMULATIVE DISTRIBUTION FUNCTION OF THE CHARACTERISTIC SIGN OF THE GAS ENVIRONMENT DURING FIRE

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1. Introduction

The number of fires in the world has a dangerous upward trend. As a result of fires, about 90 thousand people die an-

nually [1]. Fires occur in ecosystems [2], in production [3, 4], as well as at various critical infrastructure facilities [5]. The largest number of fires occurs at technical and residential facilities [6]. The special danger of such fires is due to the

fact that they occur in the premises at facilities (FPF) and pose a significant threat to human life [7]. In addition, such fires cause huge damage to the objects themselves [8, 9], the environment [10], as well as significant material damage [11]. As a result of fire, dangerous acid rain can fall [12] and pollution of aquifers can occur [13]. Therefore, the identification of thermal sources (TS) before their transition to fires at technical and residential facilities is one of the important and urgent problems.

2. Literature review and problem statement

Most current research tackles various aspects of extinguishing already existing FPF. Paper [14] considers aspects of extinguishing FPF with finely dispersed water. The use of a pulsed high-speed jet of liquid for extinguishing is considered in [15]. The physical aspects of the spread of pollution from the nuclear industry are considered in [16]. However, in [14–16], the features of the detection of TSs in order to prevent FPF at an early stage of development are not considered. In [17], the dynamics of hazardous parameters of the gas environment of premises (GEP) are investigated. Following [17], to identify TS in the premises at facilities, it is advisable to use the dynamics of increments of hazardous parameters of GEP. However, work [18] indicates that the dynamics of hazardous parameters and their increments for GEP with FPF are individual. In general, they are characterized by a nonlinear and stochastic character, being uncertain and non-stationary. The application of known linear technologies to identify thermal sources under such conditions will lead to significant errors [19]. Paper [20] notes that the nature of the dynamics of GEP is of particular importance for the reliable detection of TSs. For example, it is proposed to overcome the uncertainty and non-stationary nature of the GEP parameters in identifying TSs on the basis of self-tuning technology [21]. However, in [21], the self-adjustment technology is based on average values of the GEP parameters. The results of the experimental test of the self-tuning technology proposed in [21] are reported in [22]. Studies are limited only to the analysis of the dynamics of self-adjustment of the threshold and the assessment of the current probability of detecting TS [23]. However, all probabilistic characteristics of the dynamics of the GEP parameters contained in the sample cumulative distribution function are not considered for the detection of TS in [18–23]. Work [24] indicates the possibility of using various methods of nonlinear dynamics to detect TS under conditions of uncertainty, randomness, and non-stationarity of dynamics of hazardous parameters of GEP. Paper [25] reports studying the method of correlation dimensionality. In [26], the correlations of the main dangerous parameters of GEP are investigated. The method of adaptive calculation of recurrence plots in the case of uncertainty and non-stationarity of the dynamics of hazardous parameters of GEP is proposed in [27]. However, in [25–27], the selective cumulative function of the distribution of the dynamics of hazardous parameters and the features of its application for the detection of TS are not considered. In [28], methods for detecting TS based on the dynamics of hazardous parameters of GEP in the event of FPF are proposed. However, the proposed methods are suitable only in the case of stationary dynamics and are based on the averaged energy characteristics of hazardous parameters. Methods of temporary localization of dangerous parameters of GEP are considered in [29].

However, a selective cumulative function of the distribution of hazard dynamics for the detection of TS is not considered. In [30], a method for forecasting FPF based on the dynamics of hazardous parameters of GEP is proposed. The method of short-term forecasting of FPF based on the recurrent state of GEP is proposed in [31]. However, in [30, 31], the prediction of FPF under real conditions is carried out without using the information contained in the selective cumulative function of the distribution of the dynamics of hazardous parameters. At the same time, the selective cumulative distribution function in the general case, in addition to detecting TSs, makes it possible to estimate their probability. At the same time, the dynamics of hazardous parameters of GEP in the occurrence of FPF from different TSs have a complex nonlinear and chaotic character, depending on many uncertain random factors. Various methods are known for detecting TSs. Most of the methods are complex, have limited sensitivity and efficiency of detecting a fire. Methods of nonlinear dynamics of hazardous parameters of GEP should be considered more constructive for detecting TS [32]. However, no work has been identified that would consider methods for detecting fire TS based on a selective cumulative distribution function for various signs of increments of the state of the gas environment of the premises. These methods, being non-parametric, will make it possible to detect TS FPF under conditions of great uncertainty. Therefore, an important and unsolved part of the task to detect TS FPF under uncertainty is the application of the selective cumulative function of the distribution of the dynamics of the characteristic feature for increments of the state of GEP at the appearance of TS.

3. The aim and objectives of the study

The purpose of this work is to determine the type of empirical cumulative distribution function for the dynamics of the characteristic feature of increments of the state of the gas medium when a thermal source of fire appears in the room.

The results of the study will make it possible in practice to quickly identify the appearance of thermal sources and prevent the occurrence of fire in various types of actual facilities.

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

- to theoretically substantiate the methodology for studying the empirical cumulative function of the distribution of the dynamics of the characteristic feature of increments of the state of the gas environment when a thermal source of fire appears indoors;
- to investigate the type of empirical cumulative function of the distribution of the dynamics of the characteristic feature of increments of the state of the gas medium at two fixed time intervals before and after the appearance of various test thermal sources of fire in the laboratory chamber.

4. The study materials and methods

The object of this study is the dynamics in the characteristic sign of increments of the state of GEP with the appearance of TS FPF. The subject of the study is a type of empirical cumulative function of the distribution of the dynamics of the characteristic feature of increments of the GEP state in the absence and appearance of TS FPF. The working hypothesis assumes that the appearance of TS FPF affects

the dynamics of the characteristic parameter of increments of the GEP state. As a characteristic feature of the increments of the state of GEP, an estimate of the current probability of recurrence or the corresponding non-recurrence of the increment vector is used. To determine this feature, a modified method of recurrence plots is used. The empirical cumulative distribution function under study is determined for a characteristic feature of dynamics in the form of an assessment of the dynamics of the probability of recurrence or non-recurrence of the vector of increments of the GEP state.

The studies are based on measurements of the state of the gas environment in the laboratory chamber for fire TS in the form of alcohol, wood, cellulose, and textiles [17]. The state of the gaseous medium was determined by the measured values of smoke density, mean volumetric temperature, and CO concentration [33]. Measurements of hazardous parameters were carried out at discrete time moments $i=0, 1, 2, \dots, 400$ with an interval of 0.1 s. Therefore, the state of the gaseous medium at time i was determined by the x_i vector, and the components of this vector were determined by the results of current measurements of the specified hazardous parameters of the gaseous medium. Smoke density was measured by the sensor TGS2442 (Japan), mean volumetric temperature – DS18B20 (Germany), and CO concentration was measured by MQ-2 (China). The ignition of a fire TS in the chamber was carried out 20–25 seconds after the start of the measurement for each hazardous parameter of the atmosphere. Papers [34–36] note that the state of GEP depends on many unknown parameters and factors. For example, the parameters of TS, premises, as well as other interfering factors. The possibilities of studying the probabilistic characteristics of state increments based on the sample cumulative distribution function are shown in [37, 38]. The studies were carried out on the basis of measurements of hazardous parameters of the gaseous medium at two different time intervals before and after the appearance of test fire TS in the chamber [39]. The duration of the intervals was determined by 100 discrete measurements of the parameters. The beginning of the first measurement interval was determined by 100 counts, and the beginning of the second – by 200 counts. The beginnings of these intervals were selected from the condition of reliable absence and the beginning of the occurrence of a fire TS in the chamber.

5. Results of studying the empirical cumulative function

5.1. Theoretical substantiation of the methodology for studying the empirical cumulative function

The research methodology is based on the representation of the state of GEP in the form of some random event associated with the appearance of a fire TS. This random event is the result of many random causes. The laws of operation of these causes are usually unknown. Therefore, it is impossible to predict in advance whether or not this event will occur – the occurrence of a fire TS. However, when measuring the current state of GEP, this event is associated with the appearance of a real random variable. This can be either the vector of the GEP state itself or its increment, or any characteristic sign of the appearance of a fire TS [17, 18]. From a probabilistic point of view, any random event is fully described by the integral (cumulative) function of the probability distribution of random variables associated with this event. A characteristic feature of the random variable X

associated with the appearance of a fire TS can be considered, for example, the relative frequency (probability) of repeated (recurrent with ε accuracy) increments of the GEP state vector at the interval under consideration [17, 18]. In this case, the integral distribution function X determines the probability of performing the inequality $X < y$, where the value y determines the given level of probability of recurrence of states $y \in (0,1)$. Supplement to the integral probability distribution function of a random variable X determines the probability of the opposite inequality $X > y$. These properties of the distribution function are the basis for justifying the research methodology.

The research methodology includes the sequential implementation of seven special procedures. The first procedure is to measure arbitrary hazardous GEP parameters. This procedure is performed using a set of appropriate measuring sensors. Based on the measurement results of each of the sensors, the current value of the GEP state vector x_i is derived, where $i = 0, 1, 2, \dots, N_s - 1$. Here, the value of N_s is determined by the maximum number of discrete measurements performed by each sensor. The second procedure involves the formation of increments for the state vector x_i at each discrete point in time in accordance with the ratio

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

The third procedure is to define the space Ω of all vectors of increments $z_i \in \Omega$ and introduce the metric $d_{i,j}$ for that space. In our case, metric $d_{i,j}$ determines the distance between an arbitrary pair of elements of space Ω according to the rule

$$d_{i,j} = |z_i - z_j|. \tag{2}$$

The fourth procedure involves determining such pairs (similar or recurrent) of the elements of space Ω for which metric (2) is less than the given value ε . This procedure is mathematically determined by the function

$$R(i, j, \varepsilon) = \text{if} \left\{ i \neq j, ZH(\varepsilon - d_{i,j}), 0 \right\}. \tag{3}$$

In expression (3), the characteristic function is

$$ZH(x) = \begin{cases} 0, & x \leq 0, \\ 1, & x > 0. \end{cases}$$

The fifth procedure implies calculating, for each discrete moment i and the given value, the ε function in the form:

$$TDR(i, \varepsilon) = \text{if} \left\{ i < 0, 0, \frac{1}{i+1} \sum_{k=0}^i R(i, i-k, \varepsilon) \right\}. \tag{4}$$

Function (4) determines the sample probability of recurrent increments of the vector of GEP states up to moment i and including it. The sixth procedure is determining the current probability of the opposite event, the probability of non-recurrence of the increments of the GEP state vector. This probability is determined on the basis of function (4) by the relation of the form:

$$TDNR(i, \varepsilon) = 1 - TDR(i, \varepsilon). \tag{5}$$

The seventh procedure is to calculate the sample cumulative distribution function (5) for an arbitrary interval of measurement moments $i \in (NI, NI+TS)$. Here, the NI value

determines the beginning of the given interval, and TS determines the duration of this interval. Therefore, the selective cumulative distribution function (5) for an arbitrary given level y , based on the measurement moments $i \in (NI, NI+TS)$, will be determined from the formula

$$F(y, \epsilon) = \frac{1}{TI} \sum_{l=NI}^{NI+TI} ZH\{y - TDNR(l, \epsilon)\}. \quad (6)$$

The calculation of the sample cumulative distribution function (6) makes it possible to investigate the probabilistic properties of the dynamics of the probability of non-recurrence of the increments of the GEP state vector for an arbitrary set time interval.

The described technique includes sequential execution of procedures (1) to (6) and makes it possible to study the type of selective cumulative function of the distribution of the dynamics of the probability of non-recurrence of increments of the vector of GEP states for arbitrary intervals of measurement time intervals of hazardous parameters. This makes it possible to use data (6) to identify real-time frequencies of FPF TS.

5. 2. Results of studying the type of empirical cumulative function

The results of the study include an assessment of the type of empirical cumulative function of the distribution of the dynamics of the probability of non-recurrence of increments of the state of the gas medium at intervals of absence and appearance of TS in the laboratory chamber. Fig. 1 shows the empirical cumulative functions of the distribution of the dynamics of the probability of non-recurrence of increments of the vector of the state of the gas medium for alcohol and cellulose at the specified measurement intervals. The red curves correspond to the absence interval, and the blue color corresponds to the interval of a fire TS presence. Similar curves for wood and textiles are shown in Fig. 2.

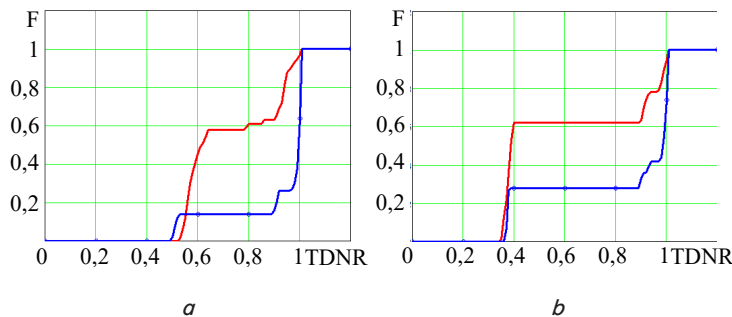


Fig. 1. Empirical cumulative functions of the distribution of the dynamics of the probability of non-recurrence (dissimilarity) of increments of the vector of the state of the gas medium at the studied intervals: a – for alcohol; b – for cellulose

Curves in Fig. 1, 2 are obtained for the given value of recurrence $\epsilon=0.01$ and take into consideration real errors of sensor measurements of hazardous parameters of the gas environment in the laboratory chamber. At the same time, the sensors used in the experiment are applied in existing fire sensors and fire alarm systems. Therefore, the results obtained can be considered reliable from a practical point of view.

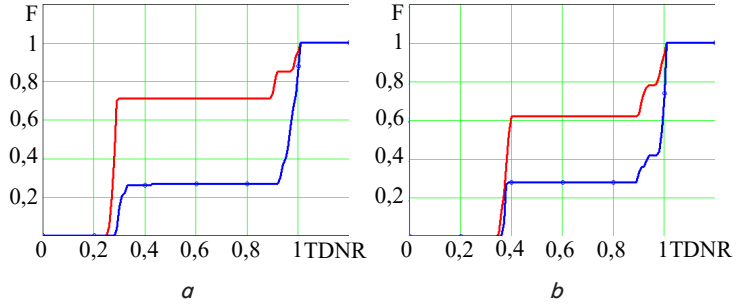


Fig. 2. Empirical cumulative functions of the distribution of the dynamics of the probability of non-recurrence (dissimilarity) of increments of the vector of the state of the gas medium at the studied intervals: a – for wood; b – for textiles

6. Discussion of results of studying the cumulative function

The results shown in Fig. 1, 2 are explained by the complex nature of the real dynamics of the probability of non-recurrence of increments of the vector of the state of the gaseous medium in the laboratory chamber for test TSs. Following Fig. 1, 2, the possible values of the empirical cumulative function of the distribution of the dynamics of the probability of non-recurrence (dissimilarity) of the increments of the vector of states of the gas medium in the chamber in the absence and in the presence of TS are not the same. For example, the lower bound for non-recurrence probability values is different. For alcohol, this boundary is determined by the probability values in the region with a center of 0.5. For cellulose, wood, and textiles, this probability boundary is defined by areas centered at 0.35, 0.27, and 0.4, respectively. This variation in boundaries is explained by the different quality of recovery of the state of the gaseous medium in the chamber after each study. Cumulative distribution functions in Fig. 1, 2 have characteristic areas of increasing and constancy of functions. The main feature of the cumulative distribution functions when fire TS test ones appear is

a decrease in the probability value for fixed regions of function values compared to the case of a reliable absence of TS. For example, for alcohol (Fig. 1, a), this probability decreases from 0.58 to 0.15, and for cellulose (Fig. 1, b) – from 0.61 to 0.29. For wood (Fig. 2, a), the specified probability decreases from 0.71 to 0.28, and for textiles (Fig. 2, b) – from 0.68 to 0.44. Following the known property of cumulative distribution functions, for intervals of fixed values, the probability of the studied random variable falling into these intervals is zero. This means that the increment probability values for alcohol and cellulose (Fig. 1) in the ranges from 0.53 to 0.9 and from 0.39 to 0.9 are zero, respectively. The values of the non-recurrence probability for wood and textiles (Fig. 2) are zero in the ranges from 0.33 to 0.93 and from 0.45 to 0.85, respectively. Areas of increasing cumulative distribution functions in Fig. 1, 2 define those possible intervals of non-recurrence probability values for which the probability is non-zero. This probability is determined by the difference in the values of the corresponding cumulative distribution functions at the boundary points of the interval of nonrecurrence probabilities values other than zero. Thus, the peculiarities of the type of empirical cumulative functions of the distribution of the dynamics

of the probability of non-recurrence (dissimilarity) of the increments of the vector of the state of the gas medium at the appearance of TS allow for early detection of fire. The main feature of this is the decrease in the values of the empirical cumulative distribution function for fixed areas of this function. For the test TS studied, the values of the empirical cumulative distribution functions for fixed regions of functions lie in the range from 0.15 to 0.44. The minimum value of 0.15 is due to TS in the form of alcohol. The maximum value of 0.44 is typical for TS in the form of textiles. This is explained by the fact that these TSs have a maximum and minimum ignition rate of the material. The limitations of this study include the finite set of fire TS tests and the use of experimental data on hazardous parameters of the gaseous medium in the laboratory chamber.

7. Conclusions

1. A method for studying the type of empirical cumulative function of the distribution of the dynamics of the probability of non-recurrence of increments of the vector of the state of the gas medium at the appearance of thermal sources of fire is proposed. The technique involves sequential execution of seven procedures. The first procedure is to measure the hazardous parameters of the gaseous medium. The second includes the formation of a vector of the state of the gaseous medium and the increments of this vector. The third is introducing a metric space for the vectors of increments of the state of the gas medium. The fourth involves the identification of recurring pairs of elements of metric space. The fifth is to calculate the current probability of recurrent increments of the vector of states of the gaseous medium. The sixth is to determine the current probability of non-recurrence of increments of the vector of states of the gaseous medium. The seventh is to calculate the sample cumulative function of the probability distribution of non-recurrence

increments of the vector of states of the gas medium for an arbitrary measurement interval. Sequential execution of the proposed procedures makes it possible to study the features of the type of selective cumulative function of the distribution of the dynamics of the probability of non-recurrence of the increments of the vector of states of the gaseous medium. This allows this selective cumulative distribution function to be used for the early detection of thermal sources of fire.

2. The empirical cumulative function of the distribution of the dynamics of the probability of non-recurrence of increments of the vector of states of the gaseous medium for two fixed time intervals of equal duration has been studied. Studies are performed for two time intervals – before and after the appearance of test thermal sources of fire in the laboratory chamber. It has been established that the features of the empirical cumulative functions of the distribution of the dynamics of the probability of non-recurrence (dissimilarity) of increments of the vector of the state of the gas medium allow for the early detection of fire. The main feature of this is a decrease in the fixed values of the empirical cumulative distribution function. It has been determined that for test thermal sources of fire, the values of the empirical cumulative distribution function lie in the range from 0.15 to 0.44. These values are explained by the different ignition rate for test thermal sources of fire. In general, the results of our studies indicate the possibility of using the empirical cumulative functions of the distribution of the dynamics of the probability of non-recurrence of increments of the vector of the state of the gas medium at various intervals for the early detection of fires.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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