Показано, що для раннього виявлення загорянь в приміщеннях можуть використовуватися методи нелінійної динаміки, що перевершують традиційні методи тимчасового, частотного або частотно-часового аналізу небезпечних факторів загоряння. Встановлено, що найбільш небезпечним при пожежах в приміщеннях є наявність чадного газу в газовому середовищі. Обґрунтовано теоретичну базу для дослідження рекурентних діаграм концентрації чадного газу в газовому середовищі. Запропоновано модифікацію рекурентних діаграм відстаней на основі ступеневих уявлень, що дозволяє селективно підкреслювати або згладжувати структурні особливості конфігурації рекурентних точок діаграм відстаней. Результати дослідження рекурентних діаграм динаміки концентрації чадного газу показують, що зазначений фактор загоряння матеріалів має в загальному випадку не стохастичну, а хаотичну динаміку. Якісно встановлено, що динаміка концентрації чадного газу в газовому середовищі має нерівномірний розподіл точок. При цьому конфігурація скупчення рекурентних точок діаграм для різних горючих матеріалів неоднакова і може бути використана для розпізнавання типу і початку раннього загоряння горючого матеріалу. Встановлений факт хаотичної динаміки концентрації чадного газу в газовому середовищі при ранньому загорянні матеріалів повинен враховуватися при розробці нових технологій надійного детектування ранніх загорянь в приміщеннях. Отримані в роботі дані важливі для більш глибокого розуміння динаміки процесу утворення чадного газу в газовому середовищі негерметичних приміщень при загорянні різних матеріалів, оскільки це пов'язано зі збереженням життя людей, які знаходяться в таких приміщеннях і своєчасною евакуацією

Ключові слова: рекурентні діаграми, концентрація чадного газу, газове середовище, негерметичні приміщення

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STUDYING THE RECURRENT DIAGRAMS OF CARBON MONOXIDE CONCENTRATION AT EARLY IGNITIONS IN PREMISES

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1. Introduction

Hazardous factors of a fire are known to have a negative influence of the environment, people, and material values. The main hazards include toxic products of combustion, flame, elevated temperature, smoke, and decreased oxygen concentration. In addition, toxic combustion products pose the greatest threat to human life, especially during fires in premises. Indeed, in modern production, household and administrative premises, there is a substantial amount of synthetic materials, which are the main sources of toxic products of combustion. There is a high content of carbon monoxide (CO) in the air during fires. The content of CO in cellars, mines, tunnels can range from 0.15 to 1.5 % and in premises, from 0.1 to 0.6 %. In this case, mortality in premises is more than 80 % of all those killed in the fires. This is explained by the fact that a person dies not from fire but from poisoning. Thus, for example, after one hour of staying in premises, the air of which contains only 0.1 % of CO the person loses consciousness. At CO concentration in premises at the level of 0.5 %, lethal poisoning occurs after 20 minutes, and at the content of 1 % – after a minute. Loss of consciousness is accompanied by such fatigue that a person who even noticed the danger is not able to escape. One of the most effective ways of preventing the dangerous influence of CO on a human is to identify ignition of materials at an early stage, which makes it relatively easy to eliminate ignition and prevent the fire development. However, early ignition of materials is characterized by complexity of processes occurring in gas medium of premises, as well as minor changes in dangerous factors, which hamper their earlier detection. Therefore, the research into dynamics of hazardous factors of a fire in the gas air medium at early ignitions in premises is a relevant problem. Given the significant danger, special attention is paid to studying the CO dynamics.

2. Literature review and problem statement

The main enemy in case of a fire, in addition to the open flame is CO. It has no color and smell. It is poisonous and is released in large amount during incomplete burning of products of combustion. Typically, incomplete combustion occurs at the lack of oxygen, which is typical for fires in premises. Paper [1] is devoted to experimental study of the fire emergence processes in premises. The results of research into processes of combustion of materials are presented in [2, 3]. Experimental study of the rate of thermal release of combustible materials in case of a fire in premises was carried out in [4]. In papers [1–4], it is indicated that the dynamics of dangerous factors of gas medium in premises in the early development of a fire is sufficiently complex, indeterminate beforehand and essentially non-stationary by nature. Studies [5, 6] focus on development of the temporal methods of determining the temperature of gas medium in premises in case of a fire. Thus, for example, paper [5] is dedicated to an increase in accuracy of determining temperature with fire sensors under actual conditions. In is proposed to improve accuracy due to selection of sensor parameter that is optimal for each case. Temperature dynamics is this case is taken into consideration by averaged statistical parameters of gas medium. A subtle structure of temperature changes in this study is not considered. Article [6] examines the method of increasing quick performance of maximal fire sensors, which also does not take into consideration the structure of temperature dynamics in premises in case of a fire. Research [7] addresses development of fire sensors that are self-adjusting by the ignitions of materials. Self-adjustment of sensors in this case it limited by the averaged characteristics of gas medium at ignitions. Paper [8] explores only dynamics of establishing the threshold and probability of ignition detection by self-adjusting fire sensors. In this case, recurrent diagrams (RD) of hazardous factors of gas medium are not considered. Paper [9] explores the temporal autocorrelations and pair correlations of dangerous factors of gas medium at ignitions in a special simulation chamber. RD of the dynamics of hazardous factors of gas medium are not explored. Specifically, RD of CO concentrations, which are important for early ignition detection, are not studied.

Analysis and procedures of measurement of random data that can be used to detect hazardous factors of gas medium in a fire are presented in [10], and mathematical reference materials are presented in [11]. However, the presented procedures are based on the stationary approach, which enables detection of only the averaged distribution of energy of hazardous factors by lags and frequencies. In this case, a subtler non-stationary structure, for example, frequency-temporal structure of hazardous factors of gas medium at early ignition is not taken into consideration.

Review of the methods of getting good temporal and frequency resolution is presented in [12]. It is noted that the problem of frequency-temporal localization has not been solved completely because of its complexity. The methods, presented in [12], are difficult for implementation of an early automatic detection and are limited to model situations that differ from actual factors of combustion. That is why they cannot be used for studying a subtle structure of CO concentration of gas medium in real time. In [13], temporal analysis of non-stationary processes is based on the Fourier transformation, which is true for stationary sections of implementation of hazardous factors of gas medium. In this case, early ignition is characterized by non-stationary sections of implementation of hazardous factors of gas medium. The structure of CO concentration in gas medium at ignitions is not considered.

Paper [14] focuses of measurement of heat and concentrations of combustion products in compartments with decreased scales. Experimental study of dynamics of combustion rate in enclosed and ventilated premises is presented in [15]. However, despite the obtained original results, there are no studies of a subtle structure of hazardous factors of ignition, in particular, CO concentration of gas medium. Article [16] deals with the experimental studies of fluctuations of gas medium parameters as early signs of ignition. At that, the results are limited to fluctuations of parameters of gas medium. The study of the actual dynamics of dangerous factors of gas medium in multi-dimensional phase space was not carried out.

Paper [17] tackles the use of general methods for analysis of the frequency-temporal representation of processes. The results of modeling and identification of nonlinear systems with the use of short-time region of Fourier transformation are presented in [18]. Application of directional short-time Fourier transformation to analysis of actual processes is discussed in [19]. In this case, the methods, presented in [17–19], appear sufficiently complex in implementation of structural solutions of the problem of fire protection of premises. Other methods of nonlinear analysis of dynamic processes, based on the approaches other than that of Fourier, are not considered. However, detection of early ignitions requires the studies of a subtler structure of the actual dynamics of dangerous factors of gas medium in multidimensional phase space. So far, there have been no such studies even for modeling experiments of decreased dimensions of premises. In this case, the known research results are limited to consideration of the current range of observed processes, while the RD are not considered. For example, study [20] discusses the application of the known frequency-temporal approach to the study of dangerous factors of early ignition in premises. General complexity and low speed of the known frequency-temporal representations are noted. The modified method of frequency-temporal representations of fluctuations of hazardous factors of gas medium at early ignitions in premises, which is characterized by high speed of detection, is proposed. Despite its high speed of detection, the proposed method is quite complex and its effectiveness in general depends on the parameters and the type of the used window functions. In addition, this method is limited to energy representation of hazardous factors of gas medium and does not make it possible to make explorations in the phase space at early ignitions in premises.

Thus, it follows from the analysis of literature that the problem of research into dynamics of hazardous factors of a fire in the gas air medium at early ignitions in premises is and remains important and relevant. Owing to the complex and non-stationary nature of dynamics of hazardous factors, frequency-temporal representations with certain restrictions have been recently used for analysis. Subsequent research is associated with examining more subtle structure of dynamics of the hazardous factors of early ignitions, based on the study of frequency-temporal representations of fluctuations of these factors. Complexity and low efficiency of these representations are noted. That is why, the search for constructive approaches and methods for analysis of dynamics of dangerous factors of gas medium at early ignitions in premises, based on modern methods of nonlinear dynamics, remains relevant. Moreover, the dynamics of CO concentration in gas medium of premises as the most dangerous factor of early ignitions has been studied insufficiently.

The known methods of nonlinear analysis appear of little use in studying the actual dynamics of CO concentration in gas medium of premises in multidimensional phase space, since they require either rather long or stationary data of observations. In addition, there are noises in actual observations.

That is why an important and unresolved part of the problem is research into dynamics of CO concentration in gas medium of premises in multidimensional phase space by actual observations that contain noise. One of the most interesting modern methods of research into nonlinear dynamic systems in multi-dimensional phase space is the RD, which got a wide theoretical development and practical recognition [21–26].

3. The aim and objectives of the study

The aim of present research is to study RD of CO concentration of gas medium by experimental data at early ignition of different types of combustible material in premises.

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

– to substantiate the theoretical base for research into recurrent diagrams of CO concentration of gas medium;

– explore RD of CO concentration of gas medium at early ignition of alcohol, paper, wood, and textiles in the chamber, simulating non-airtight premises.

4. Theoretical grounds for studying the recurrent diagrams of CO concentration in a gas medium

RD is the tool of dynamic systems analysis, which is used in various fields for objective characteristics of time series data [21–26]. For non-linear system, such as gas medium, the study of hazardous factors based on frequency-temporal representations and fast Fourier transform (FFT) appears insufficient for an objective characteristic of dynamics. That is why, RD are used in order to study the dynamics of CO concentration as the most dangerous factor of the gas medium at early ignitions in premises. RD are very important for in-depth studying and understanding of the processes of changes in CO concentration of gas medium in premises at early ignition of flammable materials. RD enable us to distinguish between possible chaotic changes in CO concentration that are deterministic by nature and those, where stochastic in nature noise prevail.

It is necessary to transform the given observation data into data of the correspondent phase space. In reconstructed phase space, proximity of two vectors of states

$$x_i = \left[y(t_i),\ y(t_i+\tau),\dots,\ y(t_i+(d-1)\tau) \right]^T$$

and

$$x_j = \left[y(t_j),\ y(t_j+\tau),\dots,\ y(t_j+(d-1)\tau) \right]^T$$

can be expressed through recurrence matrix [25]. In the case that is considered here, $y(t_i)$ is the instantaneous value of observed CO concentration of gas medium, and τ and d represent respectively the delay time and the embedding size that are selected a priori. A recurrence matrix can be estimated in different ways. The most common way of evaluation is indication of the vectors' position at a fixed distance (hypersphere of radius ε) from a certain specified vector e. A recurrence matrix in this case represents a binary matrix, determined in accordance with [25]

$$R(i,j)=H\cdot(\varepsilon-\|x_i-x_j\|), \qquad (1)$$

where (1) $H(*)$ designates indication function in the form of the Heaviside function, ε is the radius of the correspondent hypersphere, and ‖*‖ is the norm (distance). By representing graphically $R(i,j)=0$ and $R(i,j)=1$ in the form of the correspondent white and black points, as, for example, in Fig. 1, it is possible to construct RD. In this case, the RD diagonal will consist of black points, for which always $R(i,j)=1$. This diagonal is called the line of identity (LOI) and is located at the angle of 45° to coordinate axes. At this, an arbitrary separate recurrent point (i, j) will not carry the information about the states of the process at moments i and j. Only the entire totality of recurrent points (RD) makes it possible to restore the properties of the examined process – the dynamics of CO concentration. It is not possible in practice to detect complete coincidence of states in terms of a strict equation. By recurrence of CO concentration, we will imply a sufficient proximity of state x_i to state x_j. This means that states x_j that get to hypersphere of radius ε with the center in xi will be recurrent. In expression (1), all the above is described by function $H(*)$ and its parameter ε. As a norm in (1), we select norm L_∞ ($L_\infty(X)=\max|x_i|$, where xi is the i-th coordinate of arbitrary vector X), which does not depend on dimensionality of phase space, is most simple to calculate and makes it possible to explore RD theoretically, since analytic expressions for L_∞ appear simpler than for other varieties of determining norms.

RD produces important qualitative information about dynamic properties of the analyzed process. In this case, the lines that are equal in length and parallel to the LOI, characterize the periodic component of the analyzed process. The distance between the lines will determine the period of a periodic component of this process. Short sections of diagonal lines, parallel to LOI, indicate the noise periodical or quasiperiodic behavior of the process. In this case, line breaks are caused by noise. Vertical lines represent the intermittent steady behavior. Box-like RD structure (Fig. 1) corresponds to chaotic processes, and RD for stochastic processes is traditionally displayed by white and black points, distributed evenly over the entire RD area in a random way.

In the general case, the space of states of CO concentration of gas medium is multidimensional, especially when it is reconstructed based of experimental data, in which noise leads to additional increase in dimensionality of phase space. That is why the phase portrait of CO concentration can be visualized only in the form of the correspondent projections in two- or three-dimensional spaces. Therefore, RD makes it possible to explore visually a multidimensional trajectory of the state of CO concentration of gas medium through its two-dimensional representation. RD can be used on fairly short time intervals and represent repeatability of states (i. e., the frequency of visiting a small area in the phase space). Unlike other methods, such as Fourier, Wigner-Ville or the wavelet methods, RD is easy to implement and can be used for studying linear and non-linear processes [27].

It should be noted that RD is formed based on diagram $D(i,j)$, representing a symmetric matrix of dimensions $N\times N$. Here each element of the matrix represents the assigned degree α of the distance between x_i and x_j, which can be displayed on a certain color palette

$$D(i,j)=\| x_i - x_j \|^{\alpha}. \qquad (2)$$

5. Results of studying experimentally the recurrent diagrams of CO concentration in a gas medium in a chamber

The study of RD of CO concentration in the gas medium was based on the experimental data, obtained at ignition of combustible materials in the form of alcohol, paper, wood and textiles in the simulation chamber [28]. In the course of the experiment, registration of CO concentration at ignition of the specified combustible materials was produced at discrete moments t_i with the pitch of Δt=0.1 second, for i=0, 1, 2,...., 400. At this, the count number i determined the correspondent moment of time t_i of the interval of data registration. This means that for count i, the value of the observed CO concentration is determined by magnitude $y(t_i)$. Before each session of ignition of tested combustible materials, natural ventilation of the chamber was conducted. Ignition of combustible materials in the chamber was made at about the 200th count for each session. The gas sensor, applied in the existing fire detectors, was used in the chamber.

Fig. 1 shows RD of CO concentration of gas medium, determined by expression (1), for i=0, 1, 2,...., 400 and j=0, 1, 2,...., 400 at ignition of alcohol, paper, wood, and textiles in the simulation chamber in case of parameter ε=0,01. Similar RD of CO concentration of gas medium in the chamber, determined by expression (1), but for the threshold ε=0.1 are shown in Fig. 2.

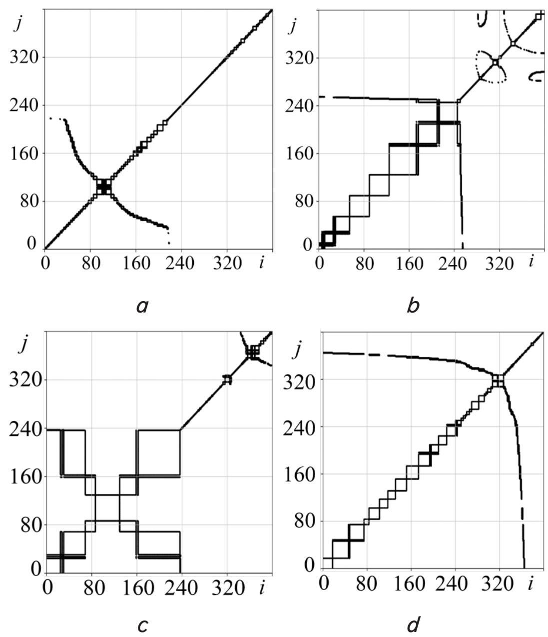

Fig. 1. Recurrent diagrams of CO concentration in a gas medium in the chamber at ε=0.01 in case of ignition: *a* – alcohol; *b* – paper; *c* – wood; *d* – textiles

RD of distances for CO concentration of gas medium in the simulation chamber at different values of α indicator in expression (2) were explored at the next stage. Fig. 3 shows, in the appropriate color palette, results of studying the distances for CO concentration of gas medium at α=1. Similar results of the study for the case of parameter α=0.5 are shown in Fig. 4. Color palette in Fig. 3 and Fig. 4 corresponds to the relative value of distances in the order of their increasing from blue (minimum relative distance) to red (maximum relative distance) for the respective counts of CO concentration of gas medium in the modeling chamber. Colored lines in Fig. 3, 4 characterize the lines of equal distances to the correspondent moments of CO concentrations of gas medium. In this case, the figures on the specified lines correspond to specific values of these distances.

RD, presented in Fig. 1–4, were constructed taking into consideration actual errors of measurement of CO concentration of gas medium by sensors in the simulation chamber, as well as errors of conversion of measurement results into digital form for storage and subsequent processing. In this case, digitization errors are negligible compared to measurement errors. That is why within a technical error of expressions (1) and (2), the reduced RD reliably estimate differences for the studied combustible materials, taking into consideration errors of CO concentration measurement by the gas sensor. Assuming the sensors used are applied in actual fire detectors, it is possible to argue about the adequacy of results, obtained when studying RD, to actual conditions.

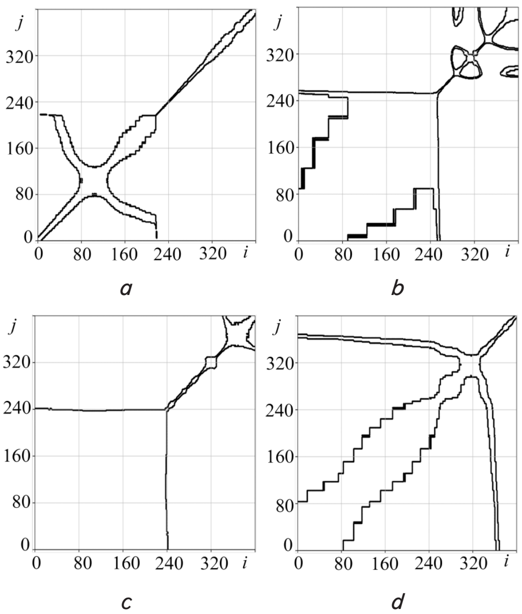

Fig. 2. Recurrent diagrams of CO concentration of gas medium in the chamber at ε=0.1 in case of ignition: *a* – alcohol; *b* – paper; *c* – wood; *d* – textiles

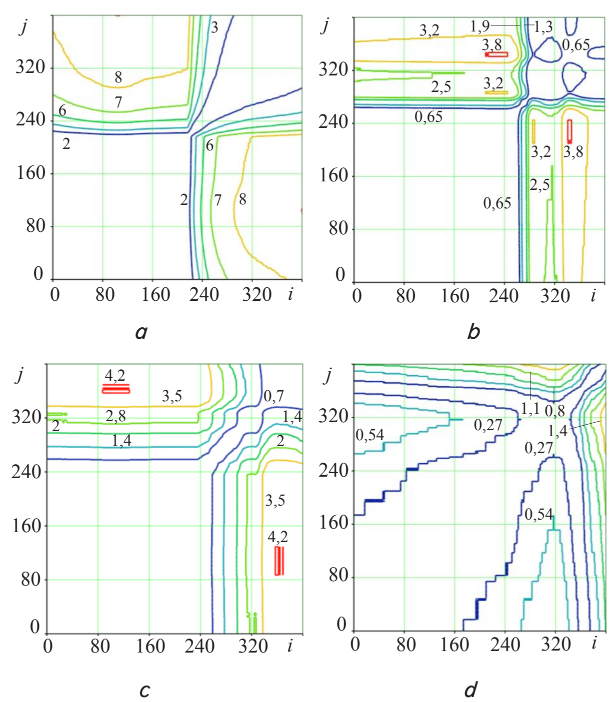

Fig. 3. Recurrent diagrams of distances for CO concentration of gas medium at α=1 in case of ignition: *a* – alcohol; *b* – paper; *c* – wood; *d* – textiles

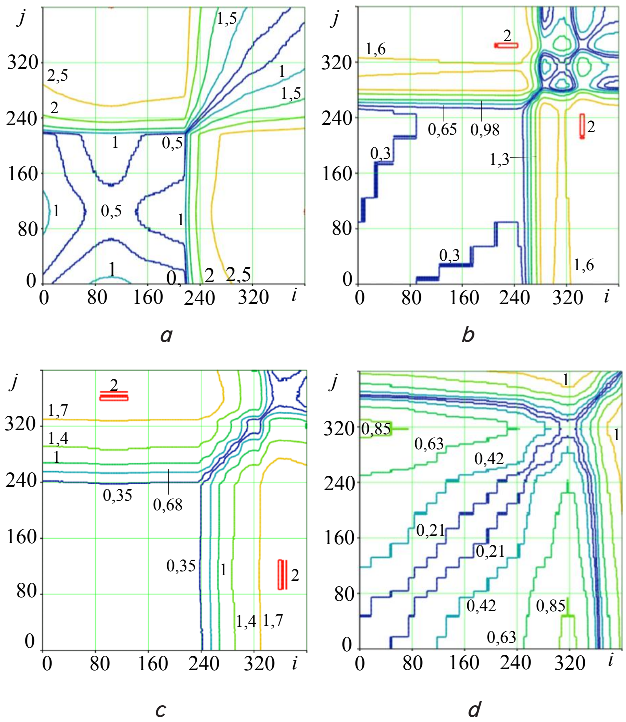

Fig. 4. Recurrent diagrams of distances for CO concentration of gas medium in the chamber at α=0.5 in case of ignition: *a* — alcohol; *b* — paper; *c* — wood; *d* — textiles

6. Discussion of results of studying the recurrent diagrams of CO concentration in a gas medium

Illustration of the results in Fig. 1–4 indicates the possibilities of making use of RD for in-depth research into dynamics of CO concentration of gas medium at early ignitions of flammable materials in premises. An important feature of the RD is simplicity of implementation, which provides high efficiency of obtaining information. This means that RD can be used in line with the actual pace of monitoring the CO concentration in a gas medium.

Analysis of results of the study shown in Fig. 1–4 makes it possible to conclude that the structure of RD depends on combustible materials and their early ignition. In addition, it is possible to distinguish two main classes of structures: topology, corresponding to large-scale structures, and texture, corresponding to small-scale structures of diagrams.

RD produce important qualitative information about dynamic properties of the analyzed process. In Fig. 1, the structure of RD in the interval of absence of ignition (approximately the first 200 counts) is characterized by the evolution of box-like structures, corresponding to transition from some chaotic processes to the others. In this case, parameters of chaotic processes change over time. Single, separately located points of the diagram characterize chaotic states of CO concentration of gas medium that are rare or unstable in time or due to strong fluctuations. Vertical and horizontal lines (Fig. 1, *b*) or close to them (Fig. 1, *d*) indicate the laminar nature of dynamics of CO concentration of gas medium before ignition of paper and textiles.

At the initial and subsequent moments of ignition of tested combustible materials, RD of dynamics of CO concentration in gas medium in the chamber have contrasting areas and characteristic bands, indicating the presence of chaotic dynamics along the main diagonal. The lack of uniformed distribution of points suggests that dynamics of CO concentration in gas medium at ignition of the studied materials is generally chaotic in character with the elements of insignificant stochastic nature.

An increase in radius ε of the hypersphere in (1) by the order of magnitude does not significantly alter the structure of RD of CO concentration, smoothing a subtle structure and highlighting its most essential characteristics (Fig. 2).

Analysis of structure of RD of distances, presented in Fig. 3 at α=1 as the form of the correspondent contours of equal distances taking into consideration the color palette, allows recognizing the beginning of ignition of tested combustible materials, as well as the type of combustible material. Thus, for example, white areas on the diagrams correspond to the absence of ignition. Sudden transitions of the white structure into blue one indicate the beginning of an increase in CO concentration of gas medium – the beginning of the ignition of material. The most intense changes in CO concentration out of tested combustible materials occur at ignition of alcohol (8 or more units in Fig. 3, *a*). In the case of using in (2) of exponent α=0.5, it is possible to identify the structure of CO dynamics in the absence of ignitions and somewhat smoothen the structure, corresponding to ignitions (Fig. 4). In this case, the basic character of structures of RD distances of dynamics of CO concentration of the gas chamber remains, which allows recognition of the beginning and the type of flammable material.

It should be noted that in Fig. 1–4, the areas of RD of CO concentration of gas medium, corresponding to the absence of ignition of combustible materials, have different structures. This is explained by the fact that the sequence of ignition sessions of materials was determined by the sequence – alcohol, paper, wood, and textiles. Moreover, after each session, combustion material was removed out of the chamber and the chamber was subjected to the natural process of ventilation. That is why the dynamics of CO concentration from the previous session with consideration of natural ventilation of the chamber was overlying on the structure of RD, correspondent to the absence of ignition.

This study is limited to consideration of norm L_∞ only. Other possible varieties of norms are not considered in this study. In addition, the research into RD was carried out on condition of the same values of the radius of hypersphere ε or exponent α for all observable values of CO concentration that are discrete in time. In the general case, the value of the radius of hyper-spheres and of the exponent can be selected depending on the current dynamic of the process. The problems of quantitative estimation of structures of RD of CO concentration and other related hazardous factors of gas medium at early ignitions of flammable materials in premises remained beyond consideration.

7. Conclusions

1. The theoretical grounds for studying RD of CO concentration in a gas medium were substantiated. It was shown that the methods of nonlinear dynamics, surpassing traditional methods of temporal, frequency or frequency-temporal analysis of dangerous ignition factors may be used for early detection of ignitions in premises. It was noted that the RD are the simplest and most constructive of them. Modification of the RD of distances, based of power repre-

sentation, is proposed. It was established that considered parametric RD enable real-time tracking of dynamics of CO concentration and detecting its deviation at occurrence of ignition of combustible materials in premises. It was noted that the basic parameters of regulation of sensitivity of the studied RD to detection of early ignitions are the radius of hypersphere ε or magnitude of exponent α.

2. RD of dynamics of CO concentration of gas medium at early ignition of alcohol, paper, wood, and textiles in the chamber, simulating non-airtight premises, for two values of radius of hypersphere (ε=0.01 and 0.1) and of exponent (α=0.5 and 1.0) were studied. It was determined qualitatively that dynamics of CO concentration of gas medium at ignitions of various materials has generally not stochastic, but chaotic nature. This is explained by the fact that the RD in the case of a stochastic nature of dynamics of CO concentration would be displayed as uniformed random distribution of points on the recurrent plane. However, the results of the conducted study, presented in Fig. 1, 2, indicate non-uniformed distribution of points on the recurrent plane, as well as existence of significant areas of white color and a complex configuration of the local clustering of points.

Beyond the framework of our study is the problem of quantitative assessment of complex structures of RD of the CO concentration dynamics and other hazardous factors of a gas medium for the comprehensive reliable recognition of early ignitions of combustible materials in premises in actual situation. Solving a given problem is of great practical importance for the environmental protection of humans at the occurrence of ignitions in various premises.

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THEORETICAL AND EXPERIMENTAL ASSESSMENTS OF ACCURACY OF NON-ORTHOGONAL MEMS SENSOR ARRAYS

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Отримано теоретичну та експериментальну оцінки точності неортогональних конфігурацій МЕМС-датчиків на основі як одноосних датчиків, так і триосних вимірювальних блоків. Актуальність дослідження зумовлено можливістю використання таких конфігурацій в навігації безпілотних рухомих об'єктів. Результати було отримано на основі методів інерціальної навігації, аналітичної механіки, математичної статистики та напівнатурного моделювання. Під час досліджень було проаналізовано неортогональні конфігурації одноосних МЕМС-датчиків, включаючи матриці напрямних косинусів. Представлено неортогональні конфігурації на основі інерціальних триосних пристроїв MPU-6050 та конструктивних елементів у вигляді трикутної та чотирикутної пірамід. Отримано відповідні матриці напрямних косинусів. На відміну від відомих неортогональних конфігурацій, враховуються вимірювання усіх датчиків, що входять до складу триосних пристроїв. Надано опис взаємного розташування вимірювальних осей окремих датчиків в запропонованих конфігураціях. Отримано теоретичну оцінку неортогональних конфігурацій МЕМС-датчиків на основі одноосних та триосних вимірювачів кутової швидкості з використанням кореляційних матриць похибок вимірювань. Визначено експериментальну оцінку точності вищезгаданих конфігурацій на підставі динамічного аналізу з використанням триступеневого динамічного стенду просторових переміщень. При цьому надано графічні залежності абсолютних похибок вимірювань та наведено розрахункові значення відносної похибки вимірювання кутової швидкості. Отримані результати є корисними, оскільки вони призначені для забезпечення високоточних та надійних вимірювань, що важливо для безпілотних літальних апаратів, які наразі широко застосовуються в Україні. Результати досліджень можуть також бути застосовані для управління ракетами, що здійснюють запуск малих штучних супутників на орбіту

Ключові слова: МЕМС-датчик, неортогональна конфігурація, напрямні косинуси, динамічний аналіз, вимірювальна похибка

1. Introduction

Nowadays sensors based on micro-electromechanical systems (MEMS sensors) are widely used in the areas of navigation and motion control. Among these applications, autopilots of unmanned aerial vehicles (UAVs) and rockets designed for launching small satellites into orbit should be mentioned. These applications are characterized by the high