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ANALYSIS OF CORRELATION DIMENSIONALITY OF THE STATE OF A GAS MEDIUM AT EARLY IGNITION OF MATERIALS

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Розглянуто застосування методу нелінійних динамічних систем для аналізу і виявлення структурних особливостей динаміки приростів стану газового середовища, що генеруються ранніми загоряннями матеріалів в негерметичній камері. Метод дослідження ґрунтується на аналізі кореляційної розмірності приростів стану газового середовища при загоряннях матеріалів. Виконано теоретичне обґрунтування методу оцінювання динаміки кореляційної розмірності приростів стану газового середовища при загоряннях. Розглянутий метод оцінки кореляційної розмірності базується на обчисленні кореляційного інтегралу Грассбергера-Прокаччі, який застосовується до приростів стану газового середовища з використанням рухомого вікна фіксованої ширини. Проаналізовано динаміку кореляційної розмірності приростів стану газового середовища при ранніх загоряннях спирту, паперу, деревини і текстилю в моделюючої камері.

Встановлено, що для досліджуваного стану газового середовища при спалахах різних тестових матеріалів динаміка кореляційної розмірності лежить в межах 0,1–0,6. Відзначається, що даний факт свідчить про фрактальну структуру розглянутих приростів стану газового середовища в камері і її хаотичну динаміку при появі осередку загоряння тестових матеріалів. При цьому фрактальна структура виявляється не однаковою, що свідчить про наявність «перехідного хаосу» щодо досліджуваних станів газового середовища. Встановлено, що поточні оцінки кореляційної розмірності приростів стану в момент загоряння матеріалів мають тенденцію різкого збільшення. Даний факт може бути використаний для надійного виявлення ранніх загорянь в приміщеннях. Показано, що прирості станів газового середовища в приміщеннях характеризують його як хаотичну динамічну систему з малою фрактальною розмірністю на відміну від традиційного підходу, який передбачає газове середовище або як детерміновану, або як випадкову систему

Ключові слова: кореляційна розмірність, прирости стану, газове середовище, ранні загоряння

1. Introduction

It is known that fires are an environmental danger to all living organisms, and, above all, for the people. The negative factors of fire typically include the generation of toxic products of combustion, flame, elevated temperature, smoke and a decrease in oxygen concentration [1–3]. The greatest threat to the environment and human life, especially at fires indoors, comes from toxic combustion products. Fire load at modern facilities is usually replete with synthetical materials, which are the main sources for the release of toxic combustion products. Most often noted during fires is the high content of carbon monoxide (CO) in a gaseous medium. Statistics on casualties in fires reveals that more than 80 % of deaths occur during fires inside buildings. This is explained by the fact that at a concentration of CO in the premises at the level of 0.5 % deadly human poisoning occurs in 20 minutes, at a concentration on the level of 1 % – in one minute. An effective way to reduce the dangerous effect of gaseous medium factors on people during fire is the timely and reliable detection of the start of a material's combustion. That makes it possible to prevent the development of fire, large-scale activities for its distinguishing [4–7], as well as to avoid human casualties.

However, to reliably identify early ignition of materials inside premises has not been possible up to now. This is explained, first, by the lack of methods to detect slight changes in a gas medium at premises at the early ignition of materials. Second, by the lack of knowledge on the dynamics of processes that occur in a gas medium at early fires. Third, by the minor changes in the parameters of a gas medium at early fires, additionally masked by different fluctuations. In this regard, it is a relevant task to analyze the dynamics of the state of a gas medium, based on contemporary methods of the nonlinear dynamics of systems.

2. Literature review and problem statement

In a general case, gas medium at premises in case of fire, from the position of analysis of the state could be regarded as a complex dynamic ecosystem. Various methods from the theory of dynamic systems have been widely used recently to analyze different ecosystems [8, 9]. Ecosystem models are typically described by a system of differential equations, whose number increases with the increasing complexity of an ecosystem. In this case, the systems are known that are described by a small number of equations while demonstrating the complex dynamics. An example of such a system is the Lorentz system that describes the process of convection. A given system is described by three equations only; its dynamics, however, demonstrates the elements of "deterministic" chaos. Therefore, it is difficult, based on the dynamics of the observed state parameter (a time series), to tell the complexity of the system. In geophysics, in particular, many studies addressed the methods for a time series analysis, including the analysis from the standpoint of the theory of dynamical systems and fractal sets [9].

The process of a fire start at premises has been experimentally studied in [10]. Results of the effect of thermal radiation on heat release rate in larch are reported in [11]; the experimental study of combustion modes of various materials under external heat was performed in [12]. Experimental study of the rate of heat dissipation during a fire at premises was described in paper [13]. It is noted that the dynamics of parameters (for the process of dangerous factors formation) in a gas medium at the initial stage of fire demonstrate both a complex and non-stationary character. Improving performance speed when applying the methods for fire detection inside premises was reported in [14]. Traditional methods are considered in this case. No new methods that would be capable of detecting changes in the parameters of a gas medium at early fires were considered; the dynamics of parameters for a gas medium were not examined. The synthesis of self-adjusting methods to detect fire by sensors was addressed in paper [15]. In the process of synthesis, only the averaged parameters of a gas medium are taken into consideration. The dynamics of parameters of a gas medium at early fires indoors are neither taken into account nor analyzed. The results reported in [16] are limited to an analysis of the dynamics of the adaptive threshold and the probability of fire detection. The dynamics of gas medium parameters and their increments, as in a complex dynamic generating system at early ignition of materials, have not been studied or considered. Paper [17] deals with experimental research into temporal autocorrelations and pair-wise correlations for the dynamics of basic parameters of a gas medium at fire in the model premises.

It should be noted [17] that for the detection of fires at premises, more important are the indicators characterizing the structural peculiarities of interaction between dangerous parameters in a gas medium, rather than their integral indicators. For example, paper [18] describes methods for determining the indicators that are suitable for identifying dangerous parameters of a gas medium at fire. However, the methods from [18] are based on a stationary approach that makes it possible to identify only the averaged energy indicators for dangerous parameters for lags and frequencies. In this case, these methods fail to account for the frequency-temporal structure of the dangerous parameters for a gas medium.

A review of the methods for temporal and frequency determination is given in [19]. It is noted that the problem of the time-frequency localization remains to be fully resolved. Known methods are complex to implement, and are difficult to apply to rapidly detect fires at premises. Paper [20] considers a method to analyze the indicators of non-stationary processes based on the application of a Fourier transform to the regions of stationarity in the nonstationary processes. However, it is not always possible to select the regions of stationarity in the dynamics of dangerous parameters in a gas medium at early fires. In this case, the gas medium as a complex dynamic system that generates dangerous parameters at fires is neither considered nor analyzed.

Experimental study into dynamics of the burning rate of materials at closed and ventilated premises is reported in [21]. Despite the originality of results, [21] lacks data on the structure of interaction between dangerous parameters in a gas medium at fires indoors. Research into parameter fluctuations in a gas medium as the signs of the early fire is discussed in work [22]. However, the results reported in [22] are restricted to the analysis of traditional statistical indicators of fluctuations in the main parameters of a gas medium. No patterns in the structure of the dynamics of interaction between dangerous parameters in a gas medium in the multidimensional phase space were considered. In this case, as follows from [17–22], early fires are a source of the non-stationary violation of the original equilibrium of a gas medium indoors. Gas medium at early fire in a general case is characterized by the more complex non-linear processes of generation and subsequent interaction between its basic dangerous parameters.

General methods of the frequency-temporal representation and identification for the nonlinear systems are discussed in papers [23] and [24], respectively. A method of analysis of the nonstationary processes based on the use of a short-time Fourier transform is described in [25]. In this case, the methods discussed in papers [23–25] turn out to be rather complex to implement and cannot be applied as feasible for the early detection of fire inside premises. The papers [23–25] fail to consider the nonlinear analysis methods for dynamic processes based on approaches other than that of Fourier. Although, in order to detect an early fire, the research that is needed first and foremost must address the structure of the dynamics of generation of dangerous parameters of a gas medium in the multidimensional phase space. However, up to now, such studies have been missing, based on the available scientific literature, even for model experiments. Paper [26] considers a frequency-temporal method and its application to studying the structure of the dynamics of dangerous parameters in a gas medium at fires indoors. It is noted that a given method has high complexity and insufficient speed. The authors, therefore, proposed the modified frequency-temporal method, which is much faster. However, this method is quite complex to implement. Its effectiveness greatly depends on the type of the window functions implemented. In this case, the modified method, as an energy method, does not make it possible to explore the structure of the dynamics of dangerous parameters in a gas medium in the corresponding phase space.

Thus, because of the complexity of the structure of dynamics and interaction between dangerous parameters in a gas medium, the detection of early fire at premises employs different frequency-temporal methods. However, these methods are characterized by complexity, limited application, and lack of efficiency. In this case, more constructive and promising are the methods of nonlinear dynamics based on the fractal structure of the states of a gas medium at premises. In this regard, further research necessitates studying the dynamics of the state of a gas medium in the multidimensional phase space. Fractal analysis methods make it possible to solve at the qualitatively higher level the problems not only on an analysis of the fine structure of the dynamics of the state of a gas medium, but also on the development of methods for the effective detection of early fires at premises [27]. It is therefore an important and unresolved part of the examined problem to analyze the correlation dimensionality of the state of a gas medium in a non-sealed chamber at the ignition of typical test materials in order to subsequently determine the feasibility of using the correlation dimensionality of the state of a gas medium as a sign of the early detection of fire at premises.

3. The aim and objectives of the study

The aim of this study is to analyze the correlation dimensionality of the state of a gas medium using the ignition of typical test materials in a non-sealed chamber as an example. That would make it possible to apply the method of correlation dimensionality for the early detection of fire at premises.

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

– to substantiate the method for calculating the correlation dimensionality of the state of a gas medium at the early ignition of materials in a non-sealed chamber;

– to analyze the correlation dimensionality of the state of a gas medium at the early ignition of alcohol, paper, wood, and textiles in a non-sealed chamber.

4. Method for calculating the correlation dimensionality of the state of a gas medium and conditions for experiment

In a general case, the correlation (fractal) dimensionality (CD) is widely used to determine a measure of order in the values for processes and is a lower estimate of the Hausdorff dimensionality for a strange attractor. The considered correlation dimensionality calculation method for state $z(t)$ of a gas medium, determined by the smoke optical density, temperature of the medium, and the concentration of carbon monoxide at time t, includes several stages.

At the first stage, a continuous trajectory of state $z(t)$ of the gas medium is replaced with a set of its discrete values composed of N points $\{z_i\}$, considered in the appropriate phase space.

At the second stage, we determine for each point i along the state trajectory the magnitude of difference $x_i=z_i-z_{i+1}$ between the current i and the next $i+1$ state of the gas medium.

At the third stage, we compute, based on the obtained values for x_i, the distance $\|x_i-x_j\|$ between the respective pairs of points, using the Euclidean, or any other equivalent measure $\|*\|$.

At the fourth stage, we determined a correlation function $C_3(r)$, which is computed for the assigned finite set of N points according to expression

$$C_3(r)=N^{-2}[\text{number of pairs } (i,j) \text{, for which distance } \|x_i-x_j\|<r], \tag{1}$$

where r is the assigned magnitude of distance between a pair of points along the trajectory. A value for the correlation function (1) depends on the magnitude of r. If, at $r\to 0$, the correlation function (1) is defined by the exponential law, that is

$$C_3(r)=ar^{D_2}, \tag{2}$$

where a is a constant, and D_2 – CD, one assumes that the trajectory of increments in the state x_i of the gas medium possesses the fractal properties. In this case, with respect to (2), the magnitude of the fractal or correlation dimensionality will be defined by the slope of the straight line in graph ($\ln C_3(r)$, $\ln r$) or

$$D_2=\frac{\ln C_3(r)}{\ln r}, \text{ at } r\to 0. \tag{3}$$

It is known that the correlation function (1) can be calculated more efficiently by drawing in the phase space a sphere of radius r (or a cube) around each point x_i and by counting the number of points in each sphere, that is,

$$C_3(r)=\frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1,\, i\neq j}^{N} H\left(r-\left\|x_i-x_j\right\|\right). \tag{4}$$

In expression (4) function $H(*)$ defines the Heaviside indicator function while we choose, as a measure of $\|x_i-x_j\|$, norm L_∞. A given rule has two important practical advantages. These advantages are the independence of a given rule on the dimensionality of the examined phase space, and the simplicity of its calculation.

Since the correlation function (4) is defined by all N points $\{x_i\}$ along the trajectory of the state increments, its application to analyze the dynamics of CD is not possible. Therefore, at the fifth stage, in order to assess the dynamics of CD (3), it is proposed to compute the correlation function (4) in a rectangular window of fixed size $N_w \ll N$, which moves discretely in proportion to the current data acquisition (that is, at a real rate of the state data acquisition). In this case, the window size N_w is selected *a priori*, based on the assigned requirements to the quality of detecting early fires. In this case, it should be borne in mind that the large width of the window leads to a better smoothing, although to the larger initial delay in the evaluation of CD, while a small window width – to the worse smoothing, although less initial delay in the evaluation of CD.

During experimental evaluation of the dynamics of CD of the state of a gas medium, data on the dangerous parameters of the state are registered by appropriate sensors located in a special chamber that simulates a non-sealed premise [28]. Typical combustibles were alcohol, paper, wood, and textiles. Registration of the dangerous parameters of a gas medium was performed at discrete moments i with a step $\Delta t=0.1$ seconds. To facilitate the study, the discrete moments i were numbered from 0 to N. This means that the state of the gas medium at moment i was defined by vector $z(t_i)$ in the respective three-dimensional phase space. Prior to each session of the ignition of tested material, we performed the natural ventilation of the chamber over 5–7 minutes to restore the initial state of the gas medium in the chamber. Ignition of combustible materials in the chamber at each session during study was carried out at about count 200 from the start of data registration. The applied sensors for measuring smoke density, temperature of the medium and CO were the standard sensors used in existing regular fire detectors. These sensors were placed in the zone of a convection jet at a height of 0.8 m above the region of location of the respective combustible material.

5. Results of experimental investigation of correlation dimensionality of the state of a gas medium at early ignition of tested materials

As already mentioned, we studied the dynamics of CD increments of the gas medium state employing a method of sliding window in proportion to data acquisition (the fifth stage of the method) on the dangerous parameters of a gas medium. Fig. 1 shows results of research into the dynamics of CD at the ignition of the tested combustible materials in the chamber for parameter $r=0.0001$ for the first 400 counts of the observed data and two values for a window width N_w, equal to 20 and 40 counts.

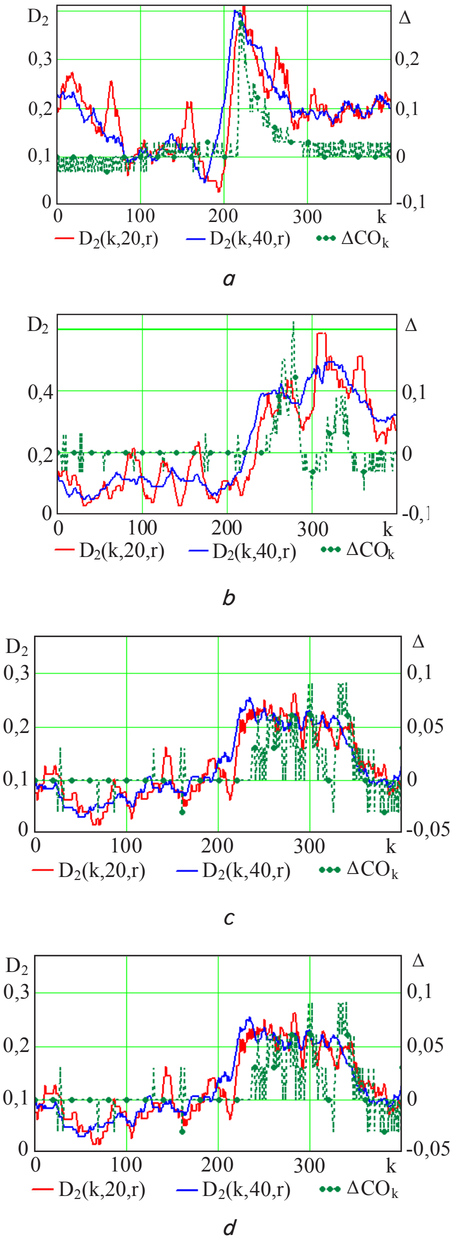

Fig. 1. Dynamics of correlation dimensionality of increments in the state of a gas medium in case of ignition: *a* – alcohol; *b* – paper; *c* – wood; *d* – textiles

Fig. 2 shows an example of the dynamics of CD of the gas medium state increments in the chamber in the case of textiles ignition at width N_w of the sliding window for 20 and 200 counts at the fixed values for magnitude $r=0.01$ (*a*) and $r=0.0001$ (*b*).

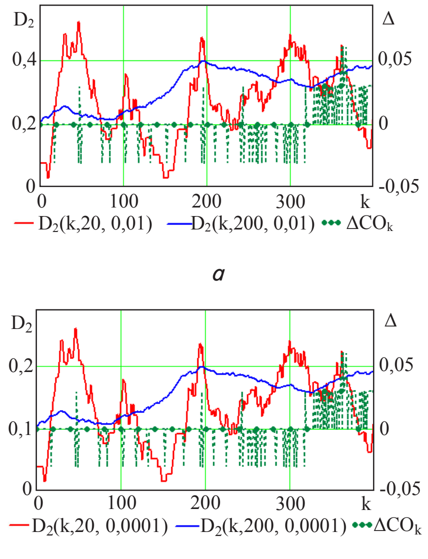

Fig. 2. Dynamics of correlation dimensionality of increments in the state of a gas medium in case of textiles ignition at values: *a* – $r=0.01$; *b* – $r=0.0001$

As an illustration of the impact of the joint increase in width N_w of the sliding window and magnitude r on estimation of the dynamics CD of increments in the state of a gas medium, Fig. 3 shows respective results in the case of textile ignition as the most common combustible material for modern premises with a low rate of ignition (such ignition is the hardest to detect).

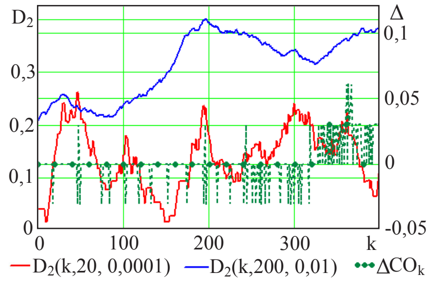

Fig. 3. Dynamics of correlation dimensionality of increments in the state of a gas medium in the case of textile ignition at the window width of 20 and 200 counts and magnitude $r=0.0001$ and $r=0.01$, respectively

Green color in Fig. 1–3 denotes the dynamics of CO concentration in the examined vector of increments in the state of a gas medium for the respective combustible material. The results obtained were derived based on the actual errors of sensors that recorded the dangerous parameters of the gas medium in the chamber, as well as errors in data digitization for their subsequent processing by a computer. In this case, it was believed that errors in the conversion of registered data into digital form were negligible compared with the errors in the sensory measurement of parameters. Therefore, the data reported reliably, within a methodological bias, estimate CD for the investigated increments in the states of a gas medium. Considering that the used sensors are applied in actual fire detectors, it may be assumed that the reported results of study into CD are adequate to actual conditions.

6. Discussion of results of studying the correlation dimensionality of increments in the state of gas medium under conditions of early fires

An analysis of the dynamics of CD increments in the state of gas medium at combustion of different tested materials indicates that it does not exceed the magnitude of 0.6. In general, this testifies to the fractal structure of the examined system in the form of a gas medium in the chamber described by the respective increments in its state, as well as its chaotic dynamics during early combustion of tested materials.

Prior to the combustion of tested materials, CD of increments in the state of a gas medium accepts values around 0.1. This means that the probability of finding two close values for the increments in the state of a gas medium is very small. Such a state is characterized as being close to random. However, at the emergence of the ignition source in the chamber, the starting dynamics of CD is characterized by a sharp increase at the moment of ignition of a material (Fig. 1, reference region 200) from 0.1 to 0.4 on average. In this case, it has been established that this is largely observed for paper (CD increases to 0.6), and to a lesser extent for textiles (CD increases to 0.3). This is explained by the different characteristics of ignition of the specified materials. The low magnitude of CD (less than 1) testifies to the existence of certain stationarity of the increments in the state of a gas medium in the chamber and to the explicit trend. In this case, it was established that a fire source in the general case seeks to disrupt the specified stationarity of increments in the state of gas medium in the chamber in the absence of fire and to change its fractal properties at the emergence of their source.

It is shown that a two-fold increase in the window size does not change the overall structure of the CD dynamics, but only leads to its somewhat smoothing (Fig. 1). In this case, all the structural features of the investigated system properties are preserved. However, it was established that an order-of-magnitude increase in the size of the window (Fig. 2) causes a significant smoothing of the CD estimate at a simultaneous more clearly identifed moment of ignition and makes it possible to detect early ignition of the materials that are difficult to detect, for example, textiles (Fig. 2, reference region 200). In this case, an increase in the radius of the sphere by an order of magnitude (Fig. 2, *a*) causes a two-fold increase in CD (from 0.2 to 0.4) without changing position of the spike along the temporal reference axis corresponding to the moment of ignition. The character of the CD dynamics in this case does not change. Illustrations of the CD dynamics, shown in Fig. 3, confirm this conclusion. A given property of the applied sliding window with a simultaneous increase in its width and radius of the sphere can be considered as a potential constructive method for the early detection of ignition at premises with combustible materials with a low ignition rate.

The main advantage of the method of CD increments in the state of a gas medium is that it is based, in contrast to those already known, on analysis of the structural dynamics of increments in the state, which make it possible to detect ignition at early stages and to apply low-cost measures to terminate them, preventing the escalation of ignition into unmanaged big fires indoors. Limitations of this study include a certain uncertainty in the selection of the window width to assess the dynamics of CD. A given limitation is temporary, since it might be eliminated or elucidated upon conducting additional field research. In addition, the application of the considered method of CD increments in the state of a gas medium in order to detect early ignition, despite the efficiency, remains difficult to implement. Further research should be directed at finding modifications to the method in order to simplify its implementation.

7. Conclusions

1. We have considered the application of the method of nonlinear dynamic systems to analyze and detect the structural patterns in the dynamics of increments in the state of a gas medium generated by the early ignition of materials in a non-sealed chamber. The research method is based on analysis of the correlation dimensionality of increments in the state of a gas medium at ignition of materials. We have theoretically substantiated the method for estimating the dynamics of correlation dimensionality of increments in the state of a gas medium during ignition. The considered method for the evaluation of CD is based on the computation of the correlation integral by Grassberger-Procaccia, applied to the gas medium state increments using a sliding window with a fixed width. That allowed us to derive a current estimate of CD increments in the state of a gas medium at ignition of flammable materials in a chamber synchronized with the observation data acquisition rate.

2. Based on the proposed method, we have analyzed the dynamics of CD increments in the state of a gas medium during early ignition of alcohol, paper, wood, and textiles in the simulation chamber. It was established that for the investigated state of the gas medium at ignition of various examined materials, the CD dynamics is within 0.1–0.6. It is noted that this fact testifies to the fractal structure of the considered increments in the state of a gas medium in a chamber and its chaotic dynamics at the occurrence of ignition sites of tested materials. In this case, the fractal structure is not uniform, which indicates the complex and transitional nature ("transitional chaos") of the investigated states of the gas medium. It was established that current estimates of CD increments in the state at the time of ignition of materials tend to a sharp increase. This fact can be used to reliably detect early fires indoors. However, beyond the scope of this study is an important problem of the "transitional chaos", characteristic of the case of detecting early ignition based on the CD increments in the state of a gas medium. Results of such a study will be reported in subsequent papers.

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