The object of this study is the dynamics of hazardous parameters of the gas environment during the ignition of materials. The problem that was solved is the early detection of fires in the premises. The research results indicate the nonlinear nature of the dynamics of hazardous parameters of the gas environment in the absence and presence of materials ignition. It was established that the bispectrum amplitude, in contrast to the amplitude spectrum of the hazardous parameters of the gas medium, contains information on the reliable detection of fires. As such information, the value of the positive dynamic amplitude range of bispectrum is used. It was established that during the ignition of alcohol, the positive dynamics of the amplitude bispectrum of all dangerous parameters of the gas medium change. Significant changes are characteristic of smoke density (from 1 dB to 30 dB) and temperature (from 1 dB to 70 dB). The dynamic range of amplitude bispectrum for CO concentration is increased from 30 dB to 70 dB. Paper ignition was found to reduce the dynamic range of the amplitude bispectrum for smoke density from 40 dB to 20 dB. At the same time, the dynamic range of amplitude bispectrum for carbon monoxide concentration and temperature increases to 60 dB. The ignition of wood causes an increase in the dynamic range of the amplitude bispectrum relative to the concentration of carbon monoxide from 40 dB to 60 dB, and the temperature – from 30 dB to 40 dB. It was established that when textiles are ignited, the range of dynamics of the amplitude bispectrum for temperature increases from 10 dB to 60 dB. The results indicate that the dynamic characteristics of the amplitudes of the bispectrum of the gas medium can be used in practice for the early detection of fires in the premises

Keywords: materials ignition, gas environment of premises, amplitude bispectrum, dynamic range, detection of fires

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PECULIARITIES OF AMPLITUDE SPECTRA OF THE THIRD ORDER FOR THE EARLY DETECTION OF INDOOR FIRES

Boris Pospelov
Doctor of Technical Sciences, Professor
Scientific-Methodical Center of Educational Institutions in the Sphere of Civil Defence
O. Honchara str., 55 a, Kyiv, Ukraine, 01601

Evgeniy Rybka
Corresponding author
Doctor of Technical Sciences, Senior Researcher
Research Center**
E-mail: e.a.ribka@gmail.com

Alexander Savchenko
PhD, Senior Researcher*

Olena Dashkovska
PhD, Associate Professor
Department of Scientific and Methodological Support For Improving the Quality of Education
Institute of Education Content Modernization
Metropolitan Vasyl Lypkivskyi str., 36, Kyiv, Ukraine, 03035

Serhii Harbuz
PhD*

Elena Naden
PhD, Associate Professor*

Ivan Chornomaz
PhD
Department of Fire Tactics and Rescue Operations
Cherkasy Institute of Fire Safety named after Chornobyl Heroes of National University of Civil Protection of Ukraine
Onoprienka str., 8, Cherkasy, Ukraine, 18034

Svitlana Hryshko
PhD***

Oleksandr Nepsha***

Dmytro Morkvin
Research Center
National Academy of the National Guard of Ukraine
Zakhysnykiv Ukrainy sq., 3, Kharkiv, Ukraine, 61001
*Department of Prevention Activities and Monitoring**
**National University of Civil Defence of Ukraine
Chernyshevska str., 94, Kharkiv, Ukraine, 61023
***Department of Physical Geography and Geology
Bogdan Khmelnitsky Melitopol State Pedagogical University
Hetmanska str., 20, Melitopol, Ukraine, 72312

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1. Introduction

The safety and stability of the functioning of various facilities are important for any state [1]. Critical infrastructure facilities are of particular importance [2]. Violation of the stability of the functioning of such objects is associated with the occurrence of various levels of dangerous events [3]. Such events are typical for most objects of the technical and environmental sphere [4, 5]. Dangerous events can also occur in various socio-economic systems [6, 7]. Fires in the premises (FP) at various facilities are particularly frequent dangerous events [8]. The particular danger of FP is associated with their significant damage to human health [9, 10], objects [11], as well as the environment [12, 13]. At the same time, as the main direction of ensuring the safety and sustainability of the functioning of various facilities, it is necessary to consider reducing damage to human health and life [14]. In this regard, the prevention of the occurrence of FP at facilities is one of the urgent problems of our times.

2. Literature review and problem statement

Paper [15] notes that as one of the constructive approaches to ensuring the sustainability of the functioning of technical facilities, the identification of FP at an early stage should be considered. At the same time, in [16] emphasis is placed on the particular importance for the detection of FP at the early stages of the analysis of various hazardous parameters of the gaseous medium (GM). However, the analysis of hazardous GM parameters in [16] is limited only to the time domain. Work [17] tackles improving the speed of the method of analysis of hazardous parameters of GM in the time domain. In this case, the method is circuit engineering, and it works only in the time domain. The frequency domain is not considered, and the circuit method concerns only the GM temperature. In [18], the non-stationary characteristics of hazardous GM parameters during fires are investigated. Adaptive approaches are proposed to identify fires under these conditions [19]. However, adaptive technologies in [19] are limited only to non-stationary energy characteristics of hazardous GM parameters and corresponding threshold adaptation. The characteristics of the hazardous parameters of GM in early fires (EF) in the premises in the frequency domain are not considered or investigated. Work [20] considers the use of group processing of data from several sensors of hazardous GM parameters and network technologies for the detection of EF [20]. The development of technology for joint processing of data on the dynamics of two or more hazardous parameters of the GM of premises in order to reliably detect EF is considered in [21]. For example, some of these technologies are already implemented in the EN and ISO standards [22–24]. Study [22] describes fire detection technology based on data from a combination of CO sensors and GM temperature. At the same time, these sensors are limited to measuring the time parameters of the GM and do not make it possible to quickly detect EF. Expansion of the functionality of the technology [22] in order to detect fires is not envisaged. Paper [23] discusses the technology of using multiple sensors to detect FP with the function of monitoring the status of sensors. However, this technology does not detect EF in the premises. It, like the technology in [22], is limited to measuring only the time parameters of GM. The ISO standard is considered in [24] as the technology of using data from CO sensor in conjunction with data from one or more thermal sensors to detect FP. However, this technology does not apply to the combined use of a CO and heat sensor with special characteristics that make it possible to detect EF in the premises. Usually, different types of smoke detectors are used to detect FP [25]. Such sensors, having high speed, have a relatively low cost. However, smoke detectors have a significant drawback associated with false detection of fires, depending on the ambient temperature [26]. For this reason, combined sensors are used to reliably detect EF, which include a gas sensor [27] and a temperature sensor [28]. In this regard, new types of sensors usually combine several sensors for various hazardous parameters [29]. To detect EF, the features of pyrolysis processes for various combustible materials (GM) and the dynamics of hazardous GM parameters are important. In [30], the characteristics of the hazardous parameters of GM during the ignition and combustion of plantation wood are investigated. Paper [31] studies the effect of the rate of heat release during combustion under various larch conditions. The study of the dependence of the rate of heat release at different intensities of wood combustion is reported in [32]. However, in [32], the studies are limited only to examining the relationship between the average rate of heat release and the intensity of combustion. The rate of heat generation at different intensities of burning of organic glass and cypress is investigated in [33]. At the same time, works [30–33] do not study the features of the spectral features of the second and third order for the current dynamics of hazardous GM parameters. Due to the objective diversity and complexity of the real dynamics of the hazardous parameters of the GM in the premises in the EF of various GM, it is necessary to apply new approaches to the study of the features of the dynamics of these parameters in EF. In this regard, studies of the features of the current dynamics of hazardous GM parameters, based on the use of modern frequency and time approaches applied in other areas, are becoming relevant. Works [34–37] consider new technologies for detecting EF, based on various fractal characteristics of hazardous parameters of the GM of premises. Thus, work [34] uses the correlation dimensionality of the vector of the state of hazardous parameters of the GM. The application of the method of recurrent diagrams for the concentration of CO in order to detect EF in the premises is considered in [35]. The use of a measure of the recurrent state vector of the GM for the short-term forecast of the FP is considered in [36]. Modification of the Brown model for FP prediction is described in [37]. The method of adaptive recurrent diagram is described in [38]. However, in [34–38], the fractal characteristics of the dynamics of hazardous GM parameters are based on the representation of GM in the form of a complex nonlinear dynamic system. The use of the recurrent diagram method for the rapid identification of hazardous air conditions is considered in [39]. The development of the correlation method for the rapid detection of recurrent states is considered in [40]. The application of the structural method for the identification of hazardous conditions of the GM is reported in [41]. The use of the uncertainty function to identify hazardous GM conditions is discussed in [42]. However, the results in those works are limited to the dynamics of dangerous parameters only in the time domain. At the same time, important features of the current dynamics of hazardous GM parameters and their state during the ignition of GM in the spectral region are not considered and investigated in those works. In [43], the instantaneous amplitude and phase frequency spectra of the dynamics of hazardous parameters of GM of the premises at the EF of various GM are investigated. It is noted that the amplitude frequency spectrums are uninformative for detecting fires. It should be noted that such a conclusion in [43] is drawn on the basis of the results of amplitude frequency spectra of the second order, which do not take into consideration the spectral correlation of frequency components characteristic of nonlinear processes. Third-order amplitude spectra that can reveal the nonlinearity of processes are not investigated. However, the second-order amplitude spectrum is determined not only by the true hazard parameter GM but also by the resulting errors accompanying specific measurements. Paper [44] notes that the optimal area for detecting EF in the premises is the ceiling area. In this regard, the role of models of dynamics of hazardous GM parameters in the ceiling area is increasing [45]. Stochastic models of hazardous GM parameters in the specified area and parameters of a random fire are considered in [46]. However, in [46], the models of the dynamics of hazardous GM parameters in the ceiling area are limited to the time domain. At the same time, [45] notes that many of the models need to be verified by experimental fire tests. In [46], on the basis of fire tests, it was established that taking into consideration the dynamics of CO concentration and smoke density makes it possible to reliably identify the EF of test sites of the EN 54 standard. The results of fire tests, taking into consideration the effects of various interfering factors, are considered in [47]. It is noted that taking into consideration the dynamics of CO concentration and smoke density makes it possible to reliably identify most of the fires. The results of an experimental study of the mutual relationships between the hazardous parameters of the GM at EF are presented in [48]. However, the reported results are limited to the evaluation of correlational relationships that take into consideration only the linear relationship. Spectral characteristics that make it possible to take into consideration other types of bonds are not considered or investigated. The analysis performed indicates that the features of the higher-order amplitude spectra for the dynamics of hazardous GM parameters in the EF in the premises are insufficiently studied. In this regard, an important and unsolved part of the problem under consideration is the experimental study of the features of the third-order amplitude spectra for the dynamics of the main hazardous parameters of the GM during fires of various GM in the premises.

3. The aim and objectives of the study

The purpose of this work is to analyze the amplitude spectra of the third order for the dynamics of the main hazardous parameters of the gas environment during the ignition of materials in the premises, which will make it possible to use their features for the early detection of fires and the prevention of fires in the premises.

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

– to substantiate studies of the third-order amplitude spectrum for an arbitrary hazardous parameter of the gaseous medium during the ignition of materials;

– to identify the features of the amplitude bispectrum of hazardous parameters of the gas environment during the ignition of materials.

4. The study materials and methods

The object of this study is the dynamics of dangerous parameters of GM at EF in GM. The main hypothesis is that there is a correlation in the spectral components of the dynamics of GM in EF GM. Identification of such correlations will make it possible to carry out EF GM, which are sources of FP. Accepted assumptions and simplifications are reduced to the assumption that the dynamics of hazardous GM parameters in EF GM in the premises is similar to the dynamics of hazardous parameters in a laboratory chamber [46]. This chamber makes it possible to simulate the dynamics of hazardous GM parameters in the ceiling area of a leaky room in the EF GM. During the experiment, alcohol, paper, wood, and textiles were used as test GMs. Temperature, smoke density, and CO concentration were considered as the gas parameters in the chamber. Temperature measurements were carried out using the TPT-4 thermal sensor (Ukraine), smoke density – using the DIP-3.2 optical smoke detector (Ukraine), as well as the CO concentration – using the Discovery series sensor (Switzerland). The results of measurements of dangerous parameters from the outputs of the corresponding sensors were stored in the computer memory. Special software made it possible to call measuring sensors at an arbitrary time interval. During the experimental study, the sensors were called at intervals of 0.1 s. Ignition of the GM in the laboratory chamber was carried out approximately at a time t_{200}, corresponding to 20 seconds from the beginning of the moment t_0 of the measurement. The study of the features of the third-order amplitude spectrum of the dynamics of the measured hazardous GM parameters in the chamber was performed for two different and identical in duration time intervals equal to 100 samples (10 s). The first interval was selected between the 100th and 200th measurements and corresponded to the absence of GM fire (normal conditions). The second interval was selected between the 200th and 300th measurements and covered the moment (beginning) of the EF of the corresponding GM in the chamber. The study was conducted sequentially for each GM in the following order: alcohol, paper, wood, and textiles. To restore the dangerous parameters of the GM in the chamber before each study, natural ventilation of the GM of the chamber was carried out for 5 minutes.

5. Results of investigating the amplitude bispectrum dynamics of the parameters of the gas medium during fires

5. 1. Substantiation of the study of the amplitude spectrum of the third order of the dangerous parameter of the gaseous medium

Higher-order spectral analysis is one of the relatively new signal processing tools used to detect and identify higher harmonics in various processes [49]. The use of third-order spectral analysis to detect ignition of electrical equipment is considered in [50]. It is noted that the detection of fires of electrical equipment is hindered by Gaussian noise, which is difficult to eliminate as an interference. Paper [51] notes that the higher-order spectrum is a powerful tool for analyzing the characteristics of non-Gaussian processes and suppressing additive Gaussian interference, and also provides more useful information compared to classical spectral power analysis. The third-order spectrum is often referred to as a bispectrum. An estimate $B(f1, f2)$ of the bispectrum, following [52], will be defined as

$$B(f1, f2) = X(f1)X(f2)X^{*}(f1+f2), \qquad (1)$$

where $B(f1, f2)$ is a function of the independent variables f1 and f2 that have the meaning of the respective frequency indices; $X(f)=\sum_{k=0}^{N-1} x(k)\exp(-j2\pi fk/N)$ $(0 \le k \le N-1)$ defines the Fourier transform for an arbitrary frequency index f ($0 \le f \le N-1$) and a given discrete set $\{x(k)\}$ of the values of the process under study; * is the operator of complex conjugation. At the same time, an arbitrary frequency index f corresponds to the frequency value of the frequency f/T in Hz. Here, the value T is determined by the interval of a given discrete set $\{x(k)\}$ in seconds. The bispectrum estimate defined by (1) is a complex value. This means that instead of (1), the corresponding estimates of the amplitude and phase of bispectrum can be considered. For the study of the third-order amplitude spectrum for an arbitrary hazardous GM parameter, it is proposed to use an estimate defined as

$$AB(f1, f2) = \\ = 10\lg\left(\left|X(f1)X(f2)X^{*}(f1+f2)\right|\right), \quad (2)$$

where $AB(f1, f2)$ is a function of variables $f1$ and $f2$ that determines the estimate of amplitude bispectrum for an arbitrary hazardous GM parameter characterized by a discrete set $\{x(k)\}$ of parameter values over a given observation interval. The estimation of amplitude bispectrum (2) is essentially instantaneous interval because it is determined by a specific parameter a discrete set $\{x(k)\}$ of the values of the hazardous parameter GM at a given interval. In this case, the estimate (2) is measured in dB, which allows for a simple transition from the assessment of the bispectrum amplitude to the assessment of the power bispectrum. The accuracy of the estimate (2) is determined by the accuracy of the estimation of the spectrum $X(f)$, determined by the interval of the discrete set $\{x(k)\}$. Following [53], with an increase in this duration, the accuracy of estimating the spectrum $X(f)$ increases. Works [54, 55] show that in the general case, for large values *of N*, the estimates of the real and imaginary parts of bispectrum (1) are asymptotically unbiased and solvent. The proposed estimate (2) is based on the use of a logarithmic function and makes it possible to give appropriate weight to different amplitudes of bispectrum (1). For example, for amplitudes smaller than one, the estimate (2) is negative. For amplitudes greater than one, the score (2) is positive. The objective of the study is to analyze the amplitude of the bispectrum of hazardous GM parameters at intervals of absence and presence of EF. Therefore, it is possible to limit the analysis of only positive values of the assessment (2) for various hazardous parameters of GM during ignition of GM. At the same time, negative values (2) corresponding to small values of the amplitude of bispectrum can be neglected.

5. 2. Features of the amplitude bispectrum dynamics of the parameters of the gas medium during the ignition of materials

The study was performed on the basis of an analysis of positive values of the score (2) at intervals of absence and presence of ignition of test GM. At the same time, the dynamic range of positive values (2) was used as an integral feature to characterize the third-order amplitude spectrum (bispectrum). Figure 1 shows diagrams of the dynamics of positive values of the bispectrum amplitude (in dB) for the studied GM parameters at the intervals of absence of fires of the corresponding GM. Similar diagrams on the intervals of GM fires are shown in Fig. 2.

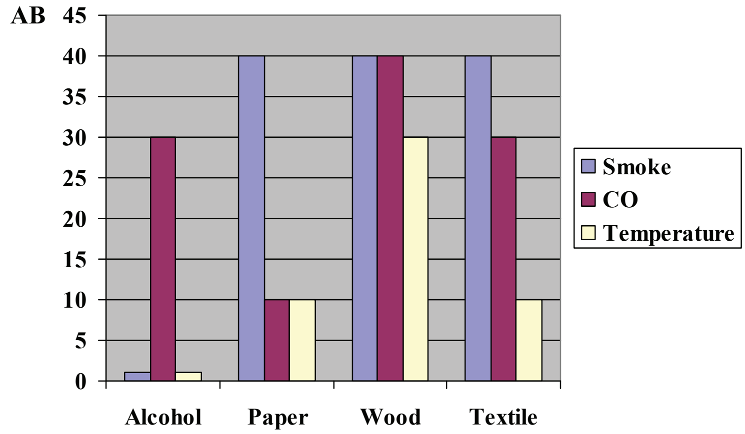

Fig. 1. Diagrams of the dynamics of positive values of the bispectrum amplitude of hazardous parameters at intervals preceding (absence) of ignition of test materials

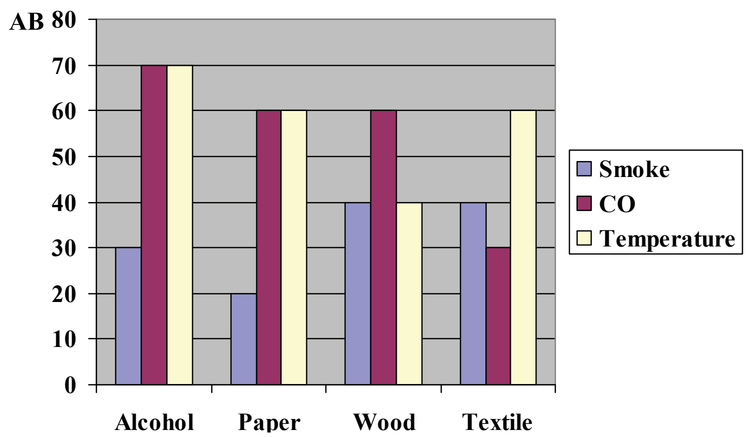

Fig. 2. Diagrams of the dynamics of positive values of the bispectrum amplitude of the studied hazardous parameters at the intervals of fires

Thus, the above (Fig. 1, 2) diagrams do not make it possible to analyze the features of amplitude bispectrum for smoke density, CO concentration, and GM temperature in the laboratory chamber at intervals of absence and presence of GM ignition.

6. Discussion of results of investigating the amplitude bispectrum of hazardous parameters of the gas medium during ignition

From the diagrams in Fig. 1, 2, it follows that the dynamics of hazardous GM parameters in the laboratory chamber at intervals of both absence and presence of fires of test GM in general has non-Gaussian statistics. In this case, the diagrams shown in Fig. 1 indicate a different level of positive dynamics of amplitude bispectrum at intervals of absence of fires of GM. This fact is explained by the peculiarities of the experiment. First, it concerns the accepted order of ignition of GM. Secondly, it is the natural ventilation of the chamber after each ignition of GM, and the final time of ventilation. At the same time, the limited ventilation time, apparently, is insufficient to fully restore the original state of GM in the chamber. The limited time of natural ventilation of the chamber is more pronounced when the original values of the dangerous parameters of GM are restored after the ignition of alcohol, paper, and wood. For example, the initial state of GM before the ignition of alcohol is characterized by a positive dynamics of amplitude bispectrum only for CO, equal to 30 dB. After burning alcohol and time-limited natural ventilation of the chamber, the state of GM in the chamber before burning paper is characterized by the positive dynamics of amplitude bispectrum for smoke, CO, and a temperature determined by 40 dB, 10 dB, and 10 dB, respectively. After burning paper and ventilation of the chamber, the residual state of GM, following Fig. 1, is characterized by the positive dynamics of amplitude bispectrum for smoke, CO, and temperature determined by 40 dB, 40 dB, and 30 dB, respectively. This means that the ignition of paper in the chamber leads to an increase in the positive dynamics of the amplitude bispectrum of CO and temperature to 40 dB and 30 dB, respectively. After the ignition of wood and the subsequent ventilation of the chamber, the residual state of the dangerous parameters of GM, following Fig. 1, is characterized by a decrease in the positive dynamics of the amplitude bispectrum for the concentration of CO and the temperature determined by 30 dB and 10 dB, respectively. From the data in Fig. 2, it follows that the dynamics of the hazardous GM parameters in the chamber at the intervals of the EF of the GM is non-Gaussian. For example, when alcohol is ignited, the positive dynamics of the amplitude bispectrum change for all GM parameters. At the same time, significant changes occur for smoke (from 1 dB to 30 dB) and temperature (from 1 dB to 70 dB). The dynamics of the amplitude bispectrum for the concentration of CO in the case of alcohol combustion increase from 30 dB to 70 dB. This means that the EF of alcohol causes significant nonlinear changes in the studied hazardous parameters of GM. Early ignition of paper, following Fig. 2, reduces the dynamics of the amplitude bispectrum of smoke from 40 dB to 20 dB. At the same time, the dynamics of the amplitude bispectrum CO and temperature increase to 60 dB. This means that the signs of the EF of paper can be the specified nature of the dynamics of the amplitude bispectrum. The EF of wood leads to an unequal change in the initial dynamics of the hazardous parameters of GM. The dynamics for smoke do not change and are characterized by a value of 40 dB. At the same time, the dynamics of the concentration of CO increase from 40 dB to 60 dB, and the temperature – from 30 dB to 40 dB. This means that a sign of the EF of wood may be an increase in the dynamics of the amplitude bispectrum of CO. When burning textiles, the dynamics of the smoke do not change and are determined by the value of 40 dB. The dynamics of CO also do not change but are characterized by a value of 30 dB. At the same time, the temperature dynamics increase from 10 dB to 60 dB. This means that the sign of the EF of textiles is an increase in the dynamics of the amplitude bispectrum of temperature.

Thus, the results of the experimental studies shown in Fig. 1, 2 indicate that the statistics of the dynamics of the dangerous parameters of the GM in the chamber at intervals of absence and presence of fires of test GM are not Gaussian. This means that in order to identify dangerous changes in the dynamics of the GM parameters caused by the EF GM, the use of spectral analysis methods of the third and higher order is required. Methods of spectral analysis of the second order are not effective enough for this. As a method of spectral analysis of the third order, the amplitude of bispectrum can be used. However, the use of the dynamic range of bispectrum amplitudes for the measurement interval does not provide information on the temporal localization of EF, which is an important practical indicator for detecting EF and preventing FP. In this case, the moment of ignition based on the dynamic range of bispectrum amplitudes at the measurement interval is determined by the time position of this interval. It should be noted that the accuracy of calculating the amplitudes of bispectrum depends mainly on the duration of the analysis interval and the sampling rate of data measurements. The longer the duration of this interval, the more accurate the calculation of the spectrum and, accordingly, the amplitude bispectrum of the dangerous GM parameter. In the study, the amplitude of bispectrum was determined for 100 data samples. The data were received at intervals of 0.1 seconds. At the same time, the duration of the intervals was 10 seconds. Therefore, the results of the study of the positive dynamics of the amplitudes of bispectrum are limited to an interval of 10 seconds. For this interval, the frequency resolution corresponds to a value of 0.1 Hz. The advantage of the study is the novelty and originality of the results associated with the use of amplitude bispectrum of the dynamics of hazardous GM parameters and the possibility of its use for the detection of EF in order to prevent FP. Therefore, it is not possible to compare the results of this seminal study with the known ones. The limitations of the study include the fact that the results were obtained on the basis of experimental measurements of hazardous GM parameters in the chamber. In this regard, verification of the results obtained requires additional fire tests taking into consideration the real GM and facility premises.

7. Conclusions

1. The substantiation of the study of the amplitude spectrum of the third order for an arbitrary dangerous parameter of the gaseous medium during the ignition of materials is carried out. The base is determining the amplitude bispectrum of the dynamics of the dangerous parameter of the gas environment during the ignition of materials in the premises. At the same time, the amplitude values of bispectrum for a given interval of the studied dangerous parameter of the gas medium are proposed to be logarithmed and formed on the basis of these values estimates of amplitude bispectrum. This makes it possible to study the features of the amplitude bispectrum of the dynamics of hazardous parameters of the gas environment for various intervals based on the analysis of the dynamic range of the amplitude bispectrum during the ignition of various materials in the premises.

2. The features of the third-order amplitude spectrum for the dynamics of the main hazardous parameters of the gas environment are investigated on the example of ignition of test materials in the laboratory chamber. The results of the studies indicate the non-Gaussian nature of the studied hazardous parameters of the gaseous environment in the absence and presence of ignition of materials. It is established that the amplitude of bispectrum, in contrast to the amplitude spectrum of hazardous parameters of the gas environment, contains information sufficient to reliably detect the appearance of fires in the premises. As such information, the value of the positive dynamic range of the amplitudes of bispectrum is used. It is established that

during the ignition of alcohol, the positive dynamics of the amplitude bispectrum change for all dangerous parameters of GM. Significant changes are characteristic of smoke density (1–30 dB) and GM temperature (1–70 dB). The dynamic range of amplitude bispectrum for CO concentration increases from 30 dB to 70 dB. It was found that paper ignition causes a decrease in the dynamic range of amplitude bispectrum for smoke density from 40 dB to 20 dB. In this case, the dynamic range of amplitude bispectrum for the concentration of CO and temperature increases to 60 dB. Wood ignition causes an increase in the dynamic range of amplitude bispectrum for the concentration of CO from 40 dB to 60 dB, and the temperature from 30 dB to 40 dB. It is established that when the textile is ignited, the dynamics range of the amplitude bispectrum for temperature increases from 10 dB to 60 dB.

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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