

The object of this study is a change in the hazardous parameters of the gas environment when materials are ignited in the premises. The subject is the features of the average bicoherence of the frequencies of the spectra of changes in the hazardous parameters of the gas environment when materials are ignited. The importance of such studies is based on the fact that the examined features can be used for the early detection of fires. The value of the average bicoherence is proposed to be determined for each frequency, taking into account the average value of the cosine argument of the complex bispectrum for a given frequency interval. It was established that the values of the average bicoherence of the spectrum of changes in the temperature of the gaseous medium in the interval of no ignition of the materials, averaged by frequency in the range of 0–2 Hz, lie in the range from –0.052 to –0.35. At the same time, the frequency-averaged values of mean bicoherence at the ignition interval of materials lie in the range of –0.128 to +0.155. Averaged in the frequency range of 0–2 Hz, the value of the mean bicoherence of the spectrum of changes in smoke density in the interval of absence of ignition of materials lies in the range from –0.018 to +0.568. In the presence of fires, this value is in the range from –0.244 to +0.23. At the same time, the average value of the average bicoherence of the spectrum of changes in the concentration of carbon monoxide of the gas medium for test materials, averaged in the range from 0 to 2 Hz, ranges from +0.016 to +0.109. In the case of ignition of materials, the average values range from +0.0007 to +0.053, except for ignition of wood (+0.117). In general, the revealed features of the average bicoherence of the frequency components of the spectra of changes in the hazardous parameters of the gas environment indicate the possibility of their use to identify fires and prevent fires

**Keywords:** mean bicoherence, complex bispectrum, change in hazardous parameters, gas environment, material ignition

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# REVEALING THE PECULIARITIES OF AVERAGE BICOHERENCE OF FREQUENCIES IN THE SPECTRA OF DANGEROUS PARAMETERS OF THE GAS ENVIRONMENT DURING FIRE

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## 1. Introduction

In the context of the constant growth of various threats, an important problem is to ensure the sustainability of the

functioning of various facilities [1]. Critical infrastructure facilities occupy a special place [2, 3] among the objects since these objects are sources of various types of threats and dangerous events [4]. Sources of threats and dangerous events

are almost all objects of the technical and environmental sphere [5, 6]. In addition, threats and dangerous events are also characteristic of most objects of the socio-economic sphere [7, 8]. Usually, any threats and dangerous events are assessed by the level of damage they cause and the frequency of their occurrence. From the point of view of the maximum frequency of occurrence and the magnitude of damage, there are threats and dangerous events caused by fires in the premises (FP) [9]. Significant damage from FP is explained both by harm to human health [10, 11] and to the objects themselves [12]. In some cases, FP also cause significant damage to the environment [13, 14]. At the same time, the world trend of increasing the frequency of FP and the damage caused by them indicates that modern technologies do not solve the problem of ensuring the stability of the functioning of objects in terms of protecting objects from FP [15]. Therefore, one of the important areas of ensuring the stability and safety of the functioning of various facilities to be considered is the protection of objects from FP. It is known that the source of any FP is ignition (Ig) [16]. This means that the protection of objects from FP is reduced to early detection of Ig and preventing their transition into fires. For this reason, early detection of fires (DF) is an urgent problem.

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## 2. Literature review and problem statement

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Paper [17] notes that early DF can be carried out through the use of unconventional measures of structural changes and their prediction for hazardous parameters of the gaseous environment (GE) of premises. However, in [17], the measures and forecasting of hazardous GE parameters are limited to considering only the time domain. It is shown that changes in hazardous parameters of GE at Ig in the general case are complex and non-stationary. In this regard, a number of areas can be identified in solving the problem of DF.

The first direction is associated with improving the quality of DF under conditions of non-stationarity of changes in hazardous GE parameters. For example, under conditions of non-stationarity of GE parameters, it is proposed to increase the speed of known methods of DF [18]. However, the increase in the performance of methods is limited only by the time domain and circuit solutions. At the same time, the frequency range and structural measures of the features of the change in the hazardous parameters of GE are not considered, and circuit solutions are limited to the consideration of the temperature parameter of GE. In [19], under conditions of non-stationary nature of hazardous GE parameters for DF, it is proposed to use adaptive methods. However, the methods proposed in [19] are based only on second-order non-stationary characteristics for hazardous GE parameters in the time domain. The frequency range and characteristics of hazardous GE parameters above the second order are not investigated.

The second direction is related to the improvement of the quality of DF under conditions of complex and non-stationary nature of changes in hazardous GE parameters. In [20], to improve the quality of DF under these conditions, it is proposed to use group processing of data from a variety of sensors, taking into account the implementation of network technologies. The method of group processing of data from a set of sensors measuring various hazardous GE parameters under difficult and non-stationary conditions is considered

in [21]. However, this method is limited to changes in GE parameters in the time domain and traditional characteristics that do not make it possible to identify features of a complex nature.

Due to the importance of DF of combustible materials (CM) with a low rate of Ig, the third direction relates to the experimental study of the features of the change in hazardous parameters of GE at Ig of such CMs. Paper [22] presents the results of studies of changes in hazardous GE parameters Ig at of wood. The study of the dependence of the rate of increase in temperature GE on the intensity of wood burning was carried out in [23]. However, these studies are limited to the dependence only for the average temperature rate and average intensity of combustion. Similar studies were performed for organic glass and cypress [24]. At the same time, [22–24] do not examine the features of the second- and third-order temporal and spectral characteristics for hazardous parameters that are capable of revealing their structural features. Given the complex nature of changes in the real hazard parameters of GE at Ig of CM, the use of unconventional approaches based on methods capable of detecting such complex changes is required for DF.

In this regard, the fourth direction is determined by studies of the possibility of DF based on the use of fractal characteristics of changes in hazardous GE parameters. Paper [25] examines the possibilities of using a correlation dimension measure for the vector of the state of hazardous GE parameter. The use of the method of recurrent plots for changes in the concentration of CO for early DF is reported in [26]. In [27], the possibilities of DF are investigated on the basis of Ig prediction, using a measure of the recurrence of the vector of the state of hazardous parameters of GE. The study of the modification of the Brown forecasting model for early DF is described in [28]. The adaptive method for calculating recurrence plots under conditions of uncertainty of hazardous GE parameters is considered in [29]. However, these methods and measures, despite their novelty and prospects of use for DF, are limited only to the time domain of change in hazardous GE parameters. The spectral region is not used. The development of a correlation method for DF based on the current recurrent state of GE is considered in [30]. The application of the method of structural function for DF is examined in [31]. The use of the uncertainty function for DF is discussed in work [32]. However, the results of studies [30–32] are limited to the consideration of the time domain. At the same time, the frequency range of change in hazardous GE parameters is not considered, and the spectral features of changes are not investigated. Most known models of changes in hazardous GE parameters are deterministic [33]. Stochastic models of changes in hazardous GE parameters are considered in [34]. However, in [33, 34], the models are temporary. At the same time, [33] notes that most models should be refined during fire tests. The results of fire tests taking into account the random factor are considered in [35]. It is noted that in order to increase the reliability of DF under real conditions, it is advisable to take into account the joint change in the concentration of CO and the density of GE smoke. In [36], the mutual relationships between the various hazardous parameters of GE are investigated. However, research is limited only to the evaluation of correlations, which characterizes exclusively linear relationships. At the same time, characteristics of the order higher than the second in the frequency domain, which make it possible to identify nonlinear relationships, are not investigated.

The fifth direction is associated with the capabilities of DF based on the peculiarities of changing the hazardous parameters of GE in the frequency domain. Paper [37] investigates the features of instantaneous amplitude and phase spectra of changes in the hazardous parameters of GE of the premises. It is noted that the amplitude spectra are uninformative for DF. However, this conclusion is made on the basis of studying the features of the amplitude spectrum of only the second order. Such a spectrum, as is known, does not make it possible to identify correlations between the corresponding frequency components, which arise in the case of nonlinear changes in hazardous GE parameters characteristic of real conditions. Features of the spectra of changes in hazardous parameters of GE of the order above the second, capable of detecting nonlinearity, are not investigated. Paper [38] investigates the features of amplitude spectra for hazardous GE parameters in a laboratory chamber. At the same time, it is shown that third-order amplitude spectra make it possible to identify nonlinear relationships of frequency components in the spectrum of change in hazardous GE parameters. It is noted that the detection of nonlinear frequency couplings is significantly dependent on the energy of the measured hazardous GE parameter. Features of bicoherence, which is invariant to the energy of a dangerous parameter, are not considered. Features of the couplings of frequency components in the spectrum of changes in hazardous GE parameters based on bicoherence are investigated in [39]. However, the features of the bicoherence of the spectrum are made only for the special case of the constituent frequencies and their second harmonics. This significantly limits the possibilities of using the results of the study for DF. At the same time, the features of the connections for an arbitrary pair of frequency components in the spectrum of changes in the dangerous parameters of GE for DF remained unexplored.

Thus, real changes in hazardous GE parameters are complex and non-stationary. In addition, these changes are due to various nonlinear effects occurring in GE at Ig, which are not predetermined. The known results of the study of the features of the coupling of frequency components in the spectrum of changes in hazardous GE parameters based on bicoherence are made only for a special case and therefore cannot be considered complete for DF. Therefore, an important and unsolved part of the problem of DF to be considered is the lack of data on the features of bicoherence for an arbitrary pair of frequency components in the spectrum of changes in the main hazardous parameters of GE at Ig of different CMs.

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### 3. The aim and objectives of the study

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The purpose of this work is to determine the features of the bicoherence of an arbitrary pair of frequency components in the spectrum of changes in the dangerous parameters of the gas environment at the intervals of absence and occurrence of ignition. The results of these studies can later be used for early detection of fires in the premises in order to prevent the occurrence of fire in them.

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

- to perform a theoretical substantiation of the study of the features of the average bicoherence for frequency components in the spectrum of changes in arbitrary hazardous parameters of the gaseous medium at a given time interval;
- to investigate the features of the average bicoherence of the frequency components of the spectrum of changes for

the main hazardous parameters of the gas environment at intervals of absence and presence of ignition of test materials.

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## 4. The study materials and methods

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The object of the study is the bicoherence of frequency components in the spectrum of changes in hazardous GE parameters in the absence and presence of Ig of CM in the room. The main hypothesis is that the values of the bicoherence of the frequency components differ in the spectrum of changes in the hazardous parameters of GE at the intervals of absence and presence of Ig. The identification of differences in bicoherence will allow them to be used for DF in order to prevent FP. Accepted assumptions and simplifications consist in the assumption that the change in the hazard parameters of GE at Ig of CMs in real premises is similar to the changes in the hazard parameters of GE in the laboratory chamber [34] for the same CMs. In the experiment, alcohol, paper, wood, and textiles were used as test CMs (TCMs). The main parameters of GE were temperature, smoke density, and CO concentration. The current measurement of GE temperature was carried out by the TPT-4 sensor (Ukraine) [40], the smoke density by the IPD-3.2 sensor (Ukraine) [41], and the CO concentration by the Discovery sensor (Switzerland) [42]. Measurements of the hazardous parameters of GE [43] were made of the ceiling area of the chamber [33], discretely with an interval of 0.1 s. The measurement results were stored in the computer's memory. Forced Ig of TCMs was performed at a discrete moment  $t_{200}$ . Features of the bicoherence of the frequency components of the spectrum of changes in the measured hazardous parameters of GE in the chamber were studied for two identical time intervals determined by 100 counts. At the same time, the first interval of the study was limited to the 100<sup>th</sup> and 200<sup>th</sup> discrete measurements and corresponded to the significant absence of Ig at the observation interval. The second interval was limited to the 200<sup>th</sup> and 300<sup>th</sup> measurements and included the moment of the beginning of the forced Ig of TCMs in the chamber. Features of bicoherence at these intervals were studied for each TCM in the following order: alcohol, paper, wood, and textiles. To restore the original values of the dangerous parameters of GE in the chamber after Ig of each TCM, natural ventilation of the chamber was carried out within 5 minutes.

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## 5. Study of frequency bicoherence in the spectra of parameters of the gas medium during fires

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### 5.1. Theoretical substantiation of the study of the average bicoherence of frequencies in the spectra of environmental parameters

It is known that spectra of the order above the second are usually used to identify and identify relationships between frequency components in nonlinear processes [44]. The use of a third-order spectrum or bispectrum for the purpose of DF of electrical equipment is considered in [45]. At the same time, [46] notes that in general, high-order spectra serve as a reliable tool identification of features of non-Gaussian processes and suppression of additive Gaussian interference. It should be noted that spectra of the order above the second contain additional information about the features of the processes compared to the spectra of the second order [47, 48].

Bispectrum  $B(h_1, h_2; T)$  for a given time interval  $T$  and a discrete set of  $\{x(k)\}$  of the values of the process under study, following [49], will be determined as

$$B(h_1, h_2; T) = X(h_1; T)X(h_2; T)X^*(h_1 + h_2; T), \quad (1)$$

where  $B(h_1, h_2; T)$  is the function of variables  $h_1, h_2$  for a given interval  $T$ ;  $h_1, h_2$  – frequency indices correspond to frequencies  $f_1 = h_1/T$  and  $f_2 = h_2/T$ ;  $X(h; T) = \sum_{k=0}^{N-1} x(k) \exp(-j2\pi hk/N)$ , ( $0 \leq k \leq N-1$ ) – defines the Fourier image for the discrete set  $\{x(k)\}$  and the arbitrary frequency index  $h$  ( $0 \leq h \leq N-1$ );  $*$  is the complex conjugation operator. The value of  $T$  determines the duration of the interval in seconds. In this case, the interval and its duration should correspond to the site of stationarity of the process. If this condition is not met, the Fourier image in (1) will be determined with an error, the magnitude of which will depend on the degree of non-stationarity of the process at this interval. In addition, the estimate (1) is a complex quantity [50]. Therefore, it is characterized by real  $\text{Re}[B(h_1, h_2; T)]$  and imaginary  $\text{Im}[B(h_1, h_2; T)]$  parts. This means that instead of estimating (1), appropriate estimates of amplitude and phase bispectrum can be considered. For a given interval  $T$ , the phase bispectrum  $\varphi(h_1, h_2; T)$  will be determined:

$$\begin{aligned} \varphi(h_1, h_2; T) &= \\ &= \arctg\{\text{Im}[B(h_1, h_2; T)] / \text{Re}[B(h_1, h_2; T)]\}. \end{aligned} \quad (2)$$

Unlike the bispectrum amplitude, (2) does not depend on the energy of the implementation segment on the finite interval of duration  $T$  and is determined by a nonlinear function on the ratio of the imaginary and real part (1), which contain approximately the same errors. This makes it possible to reduce to a certain extent the influence of these errors on the determination of bicoherence. To further reduce the effect of errors, following [39], it is proposed to use a measure instead of (2), defined as:

$$M(h_1, h_2; T) = \cos[\varphi(h_1, h_2; T)]. \quad (3)$$

In this case, the values of the bicoherence measure (3) will belong to a fixed interval:  $-1 \leq M(h_1, h_2; T) \leq 1$ . The nonlinear cosine function (2) further smoothes out random errors in the coherence region (2) (0 and  $\pi$ ). In this case, measure (3), equal to 1, corresponds to the complete coherence of the frequencies determined by the frequency indices  $h_1, h_2$ , and  $h_1 + h_2$  in the spectrum  $X(h; T)$ . If measure (3) is equal to  $-1$ , then there is complete coherence between these frequencies, characterized by a value (2) equal to  $\pi$ . In the case of measure (3) of zero, the coherence between the specified frequencies in the spectrum  $X(h; T)$  is lacking. The intermediate values of measure (3) will correspond to varying degrees of coherence of the specified frequencies in the spectrum  $X(h; T)$ . In this case, the absolute value of measure (3) for frequency indices  $h_1, h_2$ , other than zero, will indicate the presence of an appropriate degree of coherence of the frequency indices  $h_1, h_2$ , and  $h_1 + h_2$  in the spectrum  $X(h; T)$ . The degree of bicoherence determines the fraction of process energy between any pair of frequencies and their total frequency. In this case, the accuracy of measure (3) will depend on the accuracy of determining the spectrum  $X(h; T)$ , which in turn is inversely proportional to the duration of the  $T$  time interval. Following [51], with an increase in the duration

of the interval  $T$ , the accuracy of estimating the spectrum  $X(h; T)$  increases. In addition, in [52, 53] it is proved that for long duration  $T$  intervals ( $N$  values), estimates for the real and imaginary parts of bispectrum (1) are asymptotically unbiased and solvent. An important feature of measure (3), in comparison with the amplitude of bispectrum (1), is its invariance to the energy parameters of the process implementation segment, its increased accuracy and applicability to various types of types of measure frequency triplets. This makes it possible to use measure (3) to investigate the coherence of the spectral components of  $X(h; T)$  for arbitrary kinds of frequency triplets. In addition, measure (3) makes it possible to determine and visually display the degree of bicoherence of frequencies in the spectrum  $X(h; T)$  for an arbitrary hazardous GE parameter at a specified interval. Visual mapping is carried out in the form of a three-dimensional graph with two mutually orthogonal coordinate axes determined by given frequency indices, and a third mutual orthogonal axis determined by the magnitude of measure (3) for an arbitrary pair of frequency indices. However, this visual display of bicoherence makes it difficult to apply in practice. Therefore, proposals for ways to convert this display into other types of display that are more convenient for applications are relevant. Paper [39] suggests one possible way to do this. The proposed method is to convert (3) to measure  $M_1(h_1, h_1; T)$ . In this case, the proposed measure is a special case and depends only on a single frequency index. This allows the bicoherence value to be displayed for only one arbitrary frequency index in the spectrum  $X(h_1; T)$ . Therefore, this transformation of measure (3) is limited only to the determination of the amount of bicoherence between the arbitrary frequency and its doubled frequency in the spectrum of the process under study. Bicoherence for an arbitrary pair of frequencies in the spectrum, this measure does not determine. It is proposed to transform measure (3) into a measure that determines the average value of bicoherence for an arbitrary frequency, taking into account all other frequencies of the process spectrum:

$$M_2(h; T) = \text{if} \left[ h_1 = 0, 0, \frac{1}{h_{\max}} \sum_{i=1}^{h_{\max}} M(h_1, i; T) \right], \quad (4)$$

where  $h_{\max}$  is the value of the maximum frequency index in the spectrum of the process, determined from the condition:  $2h_{\max} < h_s$ , where  $h_s$  is the maximum frequency index for the frequencies in the spectrum of the process under study.

Measure (4) as opposed to  $M_1(h_1, h_1; T)$  in [39] determines the average value of bicoherence for an arbitrary frequency index, taking into account all frequencies in the spectrum corresponding to frequency indices from 0 to  $h_{\max}$ . This measure, by averaging, further reduces random errors. This enables, on the basis of measure (4), to investigate the features of the average bicoherence for an arbitrary frequency index of the spectrum of the hazardous GE parameter at arbitrary time intervals. In order to distinguish the use of measure (4) at Ig of various CMs, it is necessary to perform studies of the dynamics of the values of this measure at intervals corresponding to the reliable absence and presence of CM Ig.

Thus, measure (4), in contrast to the known measures, makes it possible to study the features not only of the average intrinsic bicoherence of frequencies in the spectrum of hazardous GE parameters but also of the average bicoherence for all frequencies in the spectrum. In other words, measure (4)

makes it possible to take into account the contribution to the energy of each of the frequencies of the studied spectrum of all frequency components.

**5. 2. Study of features of average bicoherence of frequencies in the spectra of environmental parameters during fires**

The study of the features of the average bicoherence (4) was carried out for intervals of equal duration of T of the reliable absence and presence of Ig of TCMs in the laboratory chamber. The experimental part of the work and the procedure for processing experimental data obtained in the laboratory chamber are described in detail in [39]. The difference between this procedure for processing experimental data is only that instead of a measure [39] during the experiment, a measure (4) is determined. It should be noted that measure (4) for a given duration of the time interval depends only on one arbitrary frequency index  $h1$  and determines for this index the average degree of bicoherence, taking into account the contribution of all frequency indices of the spectrum of the process. Fig. 1 presents the results of the study of mean bicoherence (4) for different values of the frequency index  $h1$  at intervals of reliable absence and presence of Ig.

Plots in Fig. 1 determine the degree of average bicoherence of frequencies in the spectrum of the corresponding hazardous GE parameters, taking into account all frequency components.

**6. Discussion of results of the study of the bicoherence of the frequencies of the parameters of the gaseous medium during fires**

From the analysis of the results in Fig. 1, it follows that the change in temperature, smoke density, and the concentration of CO of GE in the chamber at intervals of absence and presence of Ig of alcohol, paper, wood, and textiles is characterized by a different non-zero average degree of bicoherence of the frequency components in the spectrum. This means that the change in these parameters of GE in the chamber is not Gaussian but is more complex nonlinear in nature. This result coincides with the known results and generally does not contradict them. Of each of the hazardous parameters of GE considered, their complexity is not the same and individual. This is due to various complex mechanisms for the formation of changes in the considered hazardous GE parameters in the chamber at Ig of test CMs.

For example, a different value of the mean bicoherence for the frequency components in the spectrum of temperature changes GE (Fig. 1, a, b) for TCMs indicates the presence of an unequal phase relationship between an arbitrary pair of frequencies. This indicates the nonlinear nature of the formation of changes in temperature of GE both at intervals of absence and presence of Ig of CMs. Features of the average bicoherence value for certain frequencies in the spectrum of temperature changes can be used as a generalized, in contrast to the known, feature of early Ig. At the same time, in the Ig absence range, the spectrum of changes in the temperature of GE in the chamber is characterized by unequal values of the average bicoherence for individual frequency components (Fig. 1, a). For example, the average values of the average bicoherence for 20 frequency components in the frequency range 0–2 Hz lie in the range from –0.052 to –0.35. However, the maximum spread of the average bicoherence value relative to the average value for 20 frequencies takes place for paper and is from –1 to +0.8. A feature of changes in the value of the average bicoherence of frequencies in the temperature spectrum of GE for alcohol and paper in the interval of absence of Ig is their sawtooth nature. This result does not contradict the known frequent case of taking into account only the phase relationship between the frequencies and their second harmonics. The value of the average bicoherence for alcohol at a frequency of 0.1 Hz is equal to –0.9, and for paper +0.8. At the same time, in the frequency range of 0.1–1.2 Hz, changes in the average bicoherence value are linear in nature from –0.9 to +0.2. In the case of paper, the linear nature of the change from +0.8 to –1 takes place in the frequency range from 0.1 Hz to 0.7 Hz. In the interval of Ig absence of wood

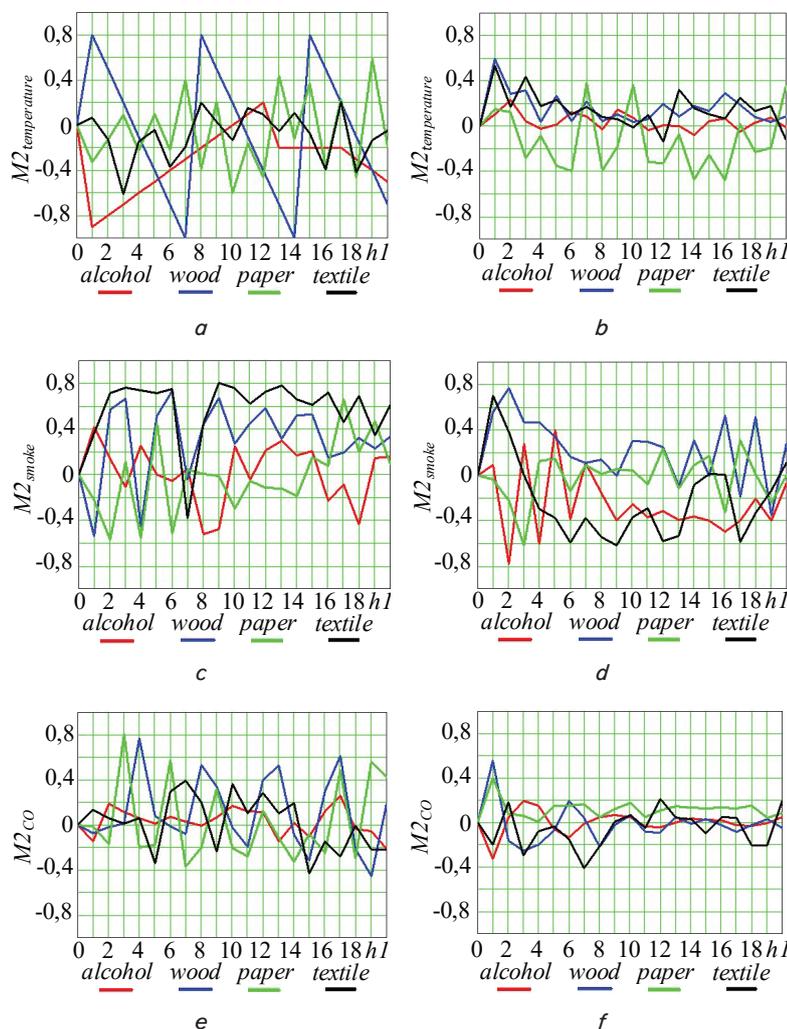


Fig. 1. Dependences of the average bicoherence of the process of temperature change, smoke density, and CO concentration for different values of the frequency index  $h1$  at different intervals: a, c, e – absence of fires; b, d, f – presence of fires

and textiles, the change in the value of the average bicoherence of GE temperature has a different and irregular structure. At the interval of Ig of CMs, temperature changes in Fig. 1 *b* are characterized by different values of the average bicoherence of frequencies in the spectrum. However, the nature of the changes in the average bicoherence value for frequencies in the spectrum differs from the case of the absence of Ig. The average value of the average bicoherence in the range of 0.1–2 Hz lies in the range from  $-0.128$  to  $+0.155$ . At the same time, the spread of the values of the average bicoherence of temperature relative to the average values in this frequency range do not exceed modulo 0.59. With alcohol Ig, the average value of bicoherence does not exceed 0.2 for all studied frequencies in the spectrum. Moreover, the maximum value of 0.2 is noted for a frequency of 0.2 Hz. For other frequencies, the value of the average bicoherence is close to zero. For paper and textiles, the nature of the change in the value of the average bicoherence is similar for frequencies exceeding 0.2 Hz, the value of the average bicoherence tends to zero values. This result does not contradict the known particular values. However, for wood, the nature of the change in average bicoherence is different. In this case, the maximum values of the average bicoherence are noted for frequencies of 0.7 and 1.0 Hz, which correspond to about 0.4. This means that at the interval of occurrence of Ig, the values of the average bicoherence of frequencies in the spectrum of temperature changes tend to small values that characterize the loss of coherence and stability of temperature changes in general. For alcohol and paper, the periodic nature of the change in the average bicoherence of frequencies in the temperature spectrum, characteristic of the case when there is no Ig, is lacking. This feature of the average bicoherence of frequencies in the temperature spectrum can be used to recognize the Ig origin of alcohol and paper.

The value of the average bicoherence of frequencies in the spectrum of smoke density changes also illustrates the fact of the presence of a phase relationship for an arbitrary pair of frequencies, which confirms the nonlinear and complex nature of the change in smoke density at intervals of absence and presence of Ig. Due to the different nature of the change in the values of average bicoherence for frequencies in the spectrum, it can be argued that the dynamics of smoke density at the intervals under consideration are not the same. The bicoherence of frequencies in the spectrum makes it possible, in contrast to the traditional Fourier spectrum, to identify individual features of the process of changing the density of smoke, both at intervals of absence and intervals of presence of Ig. At the interval of Ig absence, the spectrum of changes in smoke density in Fig. 1, *c*, the average bicoherence value is characterized by different values of the average bicoherence for individual frequencies of the spectrum. At the same time, the average deviation of the average bicoherence relative to the average value in the range of 0–2 Hz lies in the range from  $-0.018$  to  $0.568$ . At the same time, the maximum deviation of the average bicoherence relative to the average value takes place for paper in the range of 0.2–0.9 Hz, and for textiles in the two bands, 0.2–0.6 Hz and 0.9–1.6 Hz. The result does not contradict the particular case and clarifies it taking into account the presence of bicoherence for an arbitrary pair of frequencies in the spectrum of the process.

At the interval of CM Ig, the spectrum of changes in the density of GE smoke in the chamber, presented in Fig. 1, *d*, is also characterized by different values of the average bicoherence of the frequency components. In the case of Ig, the

average value of the average bicoherence of the frequencies in the range 0–2 Hz for 20 frequency components lies in the range from  $-0.244$  to  $+0.23$ . At the same time, the deviation of the average bicoherence value for the frequencies in the spectrum for all CM relative to the average value is quite large and modulo does not exceed 0.772. However, it has been established that for frequencies 0.1, 0.3, 0.5, and 0.7 Hz in the spectrum of smoke density changes at Ig of alcohol, the value of the average bicoherence is 0.1, 0.3, 0.4, and 0.1, respectively. And for frequencies 0.2, 0.4, 0.6, and 0.9 Hz, respectively,  $-0.709$ ,  $-0.6$ ,  $-0.4$ , and  $-0.4$ . In this case, in the case of Ig of paper and textiles, the value of the average bicoherence at frequencies of 0.1 and 0.2 Hz exceeds 0.7. However, for paper in the frequency range from 0.2 to 0.9 Hz, the value of the average bicoherence decreases to 0. For textiles, this value in the same frequency range decreases to  $-0.6$ . At the same time, at Ig of alcohol, the value of the average bicoherence in the frequency range from 0.1 to 0.9 Hz has different sign values in the range from  $-0.8$  to  $+0.4$ . Approximately similar are the changes in the mean bicoherence at Ig of wood. The value of the average bicoherence for the frequencies of the spectrum of change in the concentration of CO, shown in Fig. 1, *e, f*, also confirms the existence of non-zero bicoherence for an arbitrary pair of frequencies in the spectrum. This indicates the nonlinearity and complex nature of the process describing changes in the concentration of CO at intervals of absence and presence of Ig. The different nature of the change in the value of the average bicoherence in the spectra indicates the complex and individual nature of the dynamics of the concentration of CO at intervals of absence and presence of Ig. This in practice can be used to identify the features of the process of changing the concentration of CO in the absence and occurrence of Ig of CMs. On the whole, the results obtained do not contradict the known partial results but refine them taking into account the bicoherence of the frequency components in the spectrum for an arbitrary pair of frequencies. This distinguishes our results from the known ones. At the same time, the results obtained are of a general nature and can be further used for the purposes of early control of GE DF in the premises in order to prevent the occurrence of FP.

The limitation of this study is that the features of the dynamics of the average bicoherence are checked on experimental data obtained in the laboratory chamber when a certain set of test CMs is ignited. This limitation can be eliminated by conducting similar studies on experimental data of fire tests. The direction of advancement of these studies is the development of new measures of bicoherence for frequency components in the spectrum of dynamics of hazardous GE parameters in different types of premises at Ig of CMs. It should also be noted that studies devoted to the comparative analysis of known measures of bicoherence of frequency components in the spectrum of dynamics of hazardous GE parameters should be recognized as relevant.

## 7. Conclusions

1. A theoretical substantiation of the study of the features of the average bicoherence of frequency components in the spectrum of changes in an arbitrary hazardous parameter of the gas medium at a given interval is carried out. The basis of the theoretical substantiation is the determination of a complex bispectrum for changes in the dangerous pa-

parameter of the gas medium at a given time interval, followed by the calculation of its argument. The value of the mean bicoherence is proposed to be determined for each frequency on the basis of the average value of the cosine of the complex bispectrum argument for a given frequency interval. This method makes it possible to study the features of the average bicoherence of frequency components in the spectrum of changes in an arbitrary hazardous parameter of the gas medium at a given interval.

2. The features of the average bicoherence of the frequency components of the spectrum of changes in the hazardous parameters of the gas environment at intervals of absence and presence of fires of test materials in the laboratory chamber are revealed. It was found that the average values of the average bicoherence for the spectrum of temperature changes GE in the range of frequency in the range of 0–2 Hz lie in the range from –0.052 to –0.35. At the same time, the average frequency values of the average bicoherence at the interval of ignition of materials lie in the range from –0.128 to +0.155. The average value of the average bicoherence in the range of 0–2 Hz for the spectrum of smoke density changes in the interval of absence of fires lies in the range from –0.018 to 0.568. In the presence of fires, this value takes values in the range from –0.244 to +0.23. At the same time, the average value of the average bicoherence of the spectrum of changes in the concentration of CO of the gas medium in the chamber for test materials in the range of

0–2 Hz lies in the range from 0.016 to 0.109. However, in the case of ignition of materials, the average values of the average bicoherence of frequencies in the spectrum lie in the range from 0.0007 to 0.053 with the exception of wood combustion (0.117). The dynamics of the average bicoherence of the frequency components of the spectrums of changes in the corresponding hazardous parameters of the environment show that these features can be used to identify fires by the corresponding change in the hazard parameter.

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#### Conflicts of interest

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The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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#### Data availability

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All data are available in the main text of the manuscript.

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