This paper theoretically substantiates research into the spectral features of the dynamics of the main dangerous parameters of a gas environment when igniting materials in a laboratory chamber. Studying such spectral features is based on the calculation of the direct discrete Fourier transform for discrete measurements, equal in number, over the current intervals of observation of the hazardous examined parameter of the gas medium before and after the material is ignited. In this approach, a Fourier discrete transform makes it possible to determine the instantaneous amplitude and phase spectra for the time intervals under consideration. This makes it possible to explore the peculiarities of the distribution of amplitudes and phases of harmonic components in the spectrum of the dynamics of dangerous parameters of the gas environment before and after the ignition of materials. The results of experimental studies established that the nature of the amplitude spectrum is low-informative and not sensitive enough to fires. The main contribution to the amplitude spectrum of the dynamics of the investigated hazardous parameters of the gas environment in the chamber is made by the frequency components in the range of 0–0.2 Hz. The contribution to the amplitude spectrum of frequency components over 0.2 Hz is insignificant and decreases with increasing frequency. It is established that from the phase spectrum, the nature of the random scattering of phases for frequency components exceeding 0.2 Hz is informative. It was found that the nature of the phase spread for these frequency components in the spectrum depends on the type of ignition material. The results reported here could prove useful when devising new effective technologies for detecting fires in the premises of objects in various fields to protect against fires. This is explained by the fact that for the detection of fires in the premises, high-frequency components are important, characterized by the increase in dangerous parameters of the gas environment

Keywords: ignition of materials, gas environment of premises, amplitude instant spectrum, phase instantaneous spectrum

DEFINING THE FEATURES OF AMPLITUDE AND PHASE SPECTRA OF DANGEROUS FACTORS OF GAS MEDIUM DURING THE IGNITION OF MATERIALS IN THE PREMISES

Boris Pospelov
Doctor of Technical Sciences, Professor*

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

Mikhail Samoilov
Adjunct
Research Center**

Ihor Morozov
PhD, Senior Researcher
Department of Research and Organization***

Yuliia Bezuhla
PhD, Associate Professor
Department of Prevention Activities and Monitoring**

Tetiana Butenko
PhD, Senior Researcher
Department of Organization and Coordination of Research Activities*

Yuliia Mykhailovska
PhD
Research Center**

Oleksandr Bondarenko
Doctor in Public Administration Science, Associate Professor
Department of Operation Art***

Julia Veretennikova
Head of Training Laboratory
Department of Building Composite Materials and Technologies
Kharkiv National University of Civil Engineering and Architecture
Sumska str., 40, Kharkiv, Ukraine, 61002
*Scientific-methodical Center of Educational Institutions
in the Sphere of Civil Defence
O. Honchara str., 55a, Kyiv, Ukraine, 01601
**National University of Civil Defence of Ukraine
Chernyshevska str., 94, Kharkiv, Ukraine, 61023
***National Academy of the National Guard of Ukraine
Zakhysnykiv Ukrainy sq., 3, Kharkiv, Ukraine, 61001

1. Introduction

Ensuring the safety and sustainability of the functioning of various facilities is currently of particular importance for any of the states in the world [1]. This is related to resolving the common issue of sustainable development of states and world civilization as a whole [2]. The most important in addressing this task is to consider various dangerous

facilities [3]. The process of functioning of such objects is usually associated with the possibility of various dangerous events [4]. Dangerous events can occur in various premises used for both industrial and environmental activities [5]. In addition, dangerous events can occur in various socio-economic systems [6, 7]. At the same time, fires in the premises (FP) are especially dangerous and frequent events [8]. Dangerous events in the form of FPs usually cause significant damage to human life [9], objects [10], and the environment [11, 12]. In this case, the overall level of risk to human health and life is significantly increased, which reduces the sustainability of the development of civilization [13]. In this regard, the prevention of FPs should be considered at the present stage as one of the urgent problems related to the sustainable development of civilization.

2. Literature review and problem statement

Paper [14] notes that one of the constructive approaches to ensuring the sustainability of the functioning of technical facilities should be the identification of FPs at an early stage. At the same time, in work [15], emphasis is on the special importance of various hazardous parameters of the gaseous medium (GM). The cited work considers the dangerous parameters of GM, which are limited to the time range and are measured by the corresponding sensors. A method of increasing the speed of sensors of hazardous GM parameters during FP is considered in [16]. The method is limited to circuit-technical improvement of existing sensors and does not affect the spectral features of hazardous GM parameters. In this case, the method is limited only to measuring the temperature of GM. In [17], non-stationary characteristics of hazardous GM parameters are investigated. The application of adaptive technologies to detect fires under these conditions is studied in [18]. At the same time, adaptive technologies are limited to considering only non-stationary energy characteristics and are reduced to adapting the threshold of the corresponding sensors. The spectral features of the hazardous parameters of GM within premises are not considered or investigated. The use of several sensors and the use of group data processing for the early detection of fires is not considered in [19]. The development of technology for joint processing of data on the dynamics of two or more hazardous parameters of GM at premises for reliable detection of fire is considered in [20]. At the same time, some of those technologies have already been implemented in EN and ISO standards [21–23]. For example, paper [21] implements fire detection technology based on a combination of carbon monoxide and GM temperature sensors. At the same time, these sensors are limited to measuring traditional time parameters and do not make it possible to detect early fires. In addition, the expansion of the functionality of this technology is not provided. Study [22] discusses the technology of using multiple sensors to detect FP with the function of monitoring the status of sensors. However, this technology does not make it possible to detect fires in the premises. Like the technology reported in [21], it is limited to measuring only the time parameters of GM. The ISO standard [23] discusses the technology of using a carbon monoxide sensor in combination with one or more thermal sensors for use in fire detection and alarm systems. However, this technology does not apply to the joint use of a carbon monoxide and heat sensor with special characteristics that make it possible to detect indoor ignition.

Given the objective diversity and complexity of the real dynamics of the hazardous parameters of GM at premises during fires, the features of the dynamics of these parameters during the ignition of combustible materials, characterized by a different rate of burnout, remain insufficiently studied. In this regard, studies of instantaneous amplitude and phase frequency spectra of the dynamics of hazardous parameters of GM at premises during the ignition of various combustible materials are relevant.

Various types of smoke detectors are used to detect indoor fires [24]. Such sensors have high speed and have a relatively low cost. However, for these sensors, the false detection of fires depends on the temperature of GM [25]. Therefore, gas sensors [26] and temperature sensors [27] are usually used to reliably detect fires. At the same time, new types of sensors combine several sensors [28]. It is known that for the early detection of fires, the features of the pyrolysis processes of various combustible materials are important. In this regard, paper [29] examines the characteristics of hazardous factors of GM during the combustion of plantation timber. Article [30] studies the effect of the rate of heat release during combustion under various conditions of larch. The rate of heat release during the burning of wood is addressed in [31]. However, the cited study is limited to examining the relationship between the average rate of heat generation and the intensity of combustion. The rate of heat release during the combustion of organic glass and cypress is investigated in [32]. Note that [29–32] do not investigate the features of instantaneous spectral features of the dynamics of hazardous GM parameters during pyrolysis of various combustible materials in the room.

Works [33–36] consider new technologies for detecting fires that use different fractal characteristics of hazardous parameters of GM at premises. For example, study [33] proposes to use the correlation dimensionality of the vector of the state of hazardous parameters of GM at premises. The use of recurrence plots for the concentration of carbon monoxide in order to identify fires in the premises is considered in [34]. Short-term fire forecast based on the recurrent measure for the GM vector in premises and the use of Brown's zero-order model is the subject of work [35]. A method of adaptive calculation of recurrence plots is considered in [36]. However, in the cited works, the fractal characteristics of the hazard characteristics of GM parameters at premises are based on the representation of GM in the form of a complex dynamic system. The studies are limited only to considering the time domain. At the same time, the spectral features of the current dynamics of hazardous GM parameters and its state in the case of fires of materials in the premises are not considered and are not investigated.

It is known that the best area for detecting fires is the ceiling area in the premises [37]. Therefore, when devising technologies for detecting fires for the prevention of FP, the role of models for the dynamics of hazardous GM parameters in the ceiling area has recently increased [38]. Stochastic models of hazardous GM parameters in the specified area in the premises and parameters of the fire site, taking into consideration its random parameters, are considered in [39]. However, in the cited work, the models of GM hazard dynamics in the ceiling area are limited only to the time domain. At the same time, [38] notes that many of the known

models need to be comprehensively tested by experimental fire tests. In [40], based on fire tests, it was established that taking into consideration the dynamics of CO concentration and smoke density makes it possible to reliably detect fire sites of the EN 54 standard. The results of fire tests, taking into consideration the effects of various interfering factors of the GM of the premises, are considered in [41]. It is noted that taking into consideration the combined dynamics of the concentration of CO and the density of GM smoke makes it possible to reliably identify most fire sites under conditions of interfering influences. The results of an experimental study of the relationship between the hazardous parameters of the GM during the ignition of materials in the premises are given in [42]. However, the results of the study are limited to the consideration of correlational relationships that take into consideration the linear relationship. Spectral characteristics that take into consideration other types of bonds are not considered or investigated.

Our review of the scientific literature shows that the features of the amplitude and phase spectra of the dynamics of the main hazardous parameters of GM during the ignition of materials in the premises are insufficiently studied. First of all, we are talking about the results of an experimental study into the spectral features of the dynamics of hazardous GM parameters during fires. In this regard, an important and unsolved part of the problem under consideration is the experimental study of the spectral features of the dynamics of hazardous GM parameters during the ignition of various materials in the premises.

3. The aim and objectives of the study

The aim of this work is to identify the spectral features of the dynamics of the main hazardous parameters of the gas environment during the ignition of materials in the premises. This will make it possible to detect fires early and prevent fires in the premises.

To accomplish the aim, the following tasks have been set:
– to perform a theoretical substantiation of the study of the spectral features of the current dynamics of the main hazardous parameters of the gas environment during the ignition of materials;
– to investigate the amplitude and phase spectra of the current dynamics for the main hazardous parameters of the gaseous medium during the ignition of test materials in a laboratory chamber.

4. The study materials and methods

Experimental studies were conducted in a laboratory chamber [39] simulating a leaky room. The volume of the chamber was $0.524 \, m^3$. In the upper part of the chamber at a height of 0.84 m from the base, sensors were placed to measure the studied hazardous parameters of GM during the ignition of test combustible materials. Alcohol, paper, wood, and textiles were considered as test combustible materials. During ignition, the flame height for individual test combustible materials did not exceed 0.2 m. In the experiment, the dangerous parameters of GM x_i were measured using the TPT-4 heat sensor, the DIP-3.2 optical smoke detector, and the CO sensor (Discovery series).

The measured values of hazardous parameters from the outputs of the corresponding sensors were stored in the computer's memory. The developed software made it possible to call sensors at an arbitrary time interval. In the experiment, the sensors were called at intervals of 0.1 s. The ignition of test combustible materials in the chamber was carried out approximately at time t_{200} corresponding to 20 s. To study the spectral features of the dynamics of the measured hazardous parameters of GM in the chamber, two time intervals of equal duration equal to 100 counts (10 s) were selected. In this case, the first interval was selected between count 100 and count 200 and corresponded to the absence of ignition of the test material. The second interval was selected between counts 200 and 300; it covered the moment of the beginning of the ignition of the corresponding test combustible material.

The study of the spectral features of the dynamics of hazardous GM parameters at the intervals of absence and onset of ignition was carried out separately for each test material in the following sequence: alcohol, paper, wood, and textiles. During the experiment, the instantaneous amplitude and phase spectra of the dynamics of hazardous GM parameters in the laboratory chamber were investigated. To restore the initial conditions of GM in the chamber after each ignition of the test material, natural ventilation of the chamber was carried out for 5–7 minutes.

5. Results of studying the spectral features of the gas medium during the ignition of materials

5. 1. Theoretical substantiation of the study into spectral features of the gas medium during the ignition of materials

The theoretical substantiation of the study into the spectral features of the gas medium during the ignition of materials is based on the representation of the GM of the room in the form of some complex dynamic system. Inside this system, there is some site of possible ignition of the corresponding combustible material. In the case of ignition of the material, GM of the room is disturbed. These disturbances are manifested in a corresponding change in the dynamics of the hazardous GM parameters. Let the state of such a system of the system in question at an arbitrarily fixed moment in time be characterized by a predefined set of hazardous GM parameters. As hazardous GM parameters, we shall consider the average volumetric temperature, smoke density, and CO concentration. To study the spectral features of the current dynamics of hazardous GM parameters, it is proposed to use the method of direct discrete Fourier transform applied to a fixed set of discrete measurements of the studied hazard GM parameter before ignition and after ignition of the material. The direct discrete Fourier transform method for a fixed set of discrete measurements makes it possible to calculate the instantaneous spectrum for a given set of measurements. The instantaneous spectrum differs in that, unlike other spectra, it is possible to characterize the amplitude frequency composition for the studied discrete set of measurements and the instantaneous phase spectrum corresponding to these frequencies. By selecting a discrete set of measurements for another time interval of the dynamics of the hazardous GM parameter, it is possible to determine the instantaneous amplitude frequency composition and the phase spectrum corresponding to these frequencies, characteristic of this set

of measurements. This means that this approach makes it possible to investigate the spectral features of the dynamics of hazardous GM parameters during ignition by selecting an appropriate discrete set of measurements before and after the ignition of the material.

The operation of calculating the direct discrete Fourier transform is reduced to the calculation of the average values of the amplitudes and phases of discrete harmonic components determined by a specific discrete set of measurements for the studied interval of dynamics of hazardous GM parameters. For a discrete fixed size N of a measurement set $x(k)$, the instantaneous DFT $X(f)$ can be represented as follows:

$$X(f) = \sum_{k=0}^{N-1} x(k) \exp(-j2\pi f k / N) / N, \qquad (1)$$

where f, $k=0$, 1, ..., $N-1$; $X(f)$ is the DFT for an arbitrary GM parameter and a discrete frequency f; $x(k)$ is a discrete measurement at moment k for the studied interval of dynamics of an arbitrary GM parameter.

Taking into consideration (1), the value $|X(f)|$ will determine the instantaneous amplitude spectrum for the discrete frequency f, and the value $\arg[X(f)]$ – the corresponding instantaneous phase spectrum (in radians) for the discrete frequency f. In accordance with representation (1), experimental studies of the spectral features (instantaneous amplitude and phase spectrum) of the dynamics of hazardous GM parameters for fixed time intervals before and after ignition of the corresponding test material were performed. The results of our studies are given below. In the study, each discrete frequency f in (1) corresponded to a circular discrete frequency m (Hz), determined by the value $f*10/(N)$.

5. 2. Results of studying the amplitude and phase spectra of dynamics of hazardous parameters of the gaseous medium

The processing of the experimental data was carried out in accordance with the following procedures. The first procedure involved performing discrete measurements of mean volumetric temperature, CO concentration, and GM smoke density in the laboratory chamber using appropriate sensors. This procedure was performed at specified intervals of absence and presence of ignition for each test material. The second procedure was to store the measurement results in the computer's memory. The implementation of the first and second procedures was carried out using special equipment that pairs the outputs of the sensors with a computer, and the developed software that allowed the equipment to record and store the measured data. The third procedure was to calculate the amplitude and phase spectrum from the measured data according to (1). Figures 1 to 4 show the results of these calculations. The amplitude spectrum was determined by the dependence of the amplitude of the studied hazardous parameter GM (in units of measurement for the corresponding parameter) on the discrete frequency (in Hertz). The phase spectrum was determined by the dependence of the phase (in radians) on the discrete frequency (in Hertz). The implementation of the third procedure was carried out with the help of specially developed software in the Mathcad-14 programming environment.

Fig. 1 shows the amplitude and phase spectra for the mean volumetric temperature, CO concentration, and smoke density of GM in the laboratory chamber, obtained at fixed intervals before and after ignition of the test material in the form of alcohol.
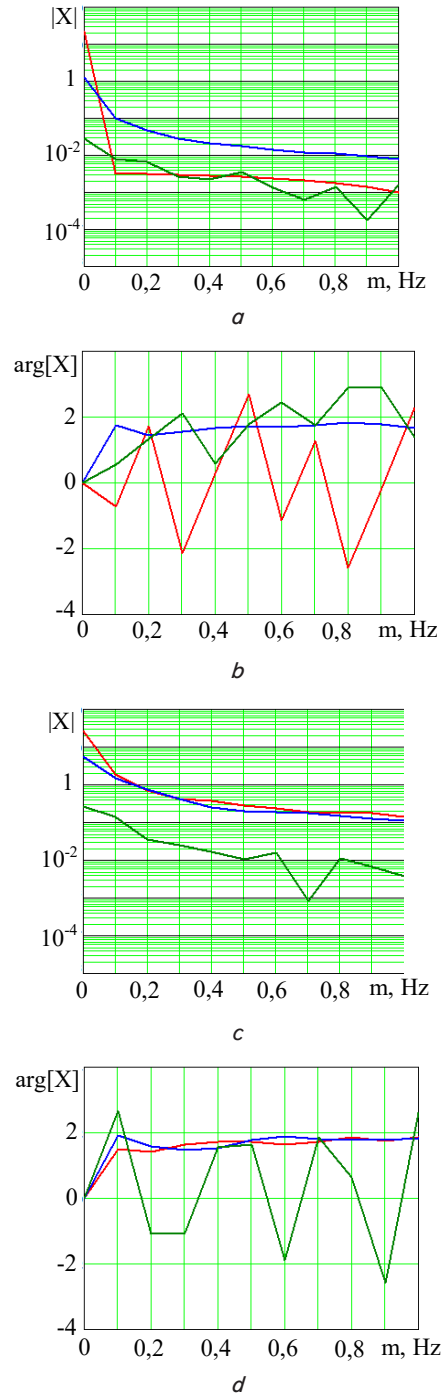

Fig. 1. Amplitude and phase spectra for the studied parameters of the gas medium in the chamber before and after the ignition of alcohol: a — amplitude spectrum in the absence of ignition; b — phase spectrum in the absence of ignition; c — amplitude spectrum during ignition; d — phase spectrum during ignition

Similar amplitude and phase spectra for the mean volume temperature, CO concentration, and smoke density of the chamber's GM before and after the start of paper ignition are shown in Fig. 2.

Fig. 3 shows the amplitude and phase spectra for the mean volumetric temperature, CO concentration, and density of smoke in the chamber's GM at the studied intervals before and after wood combustion.
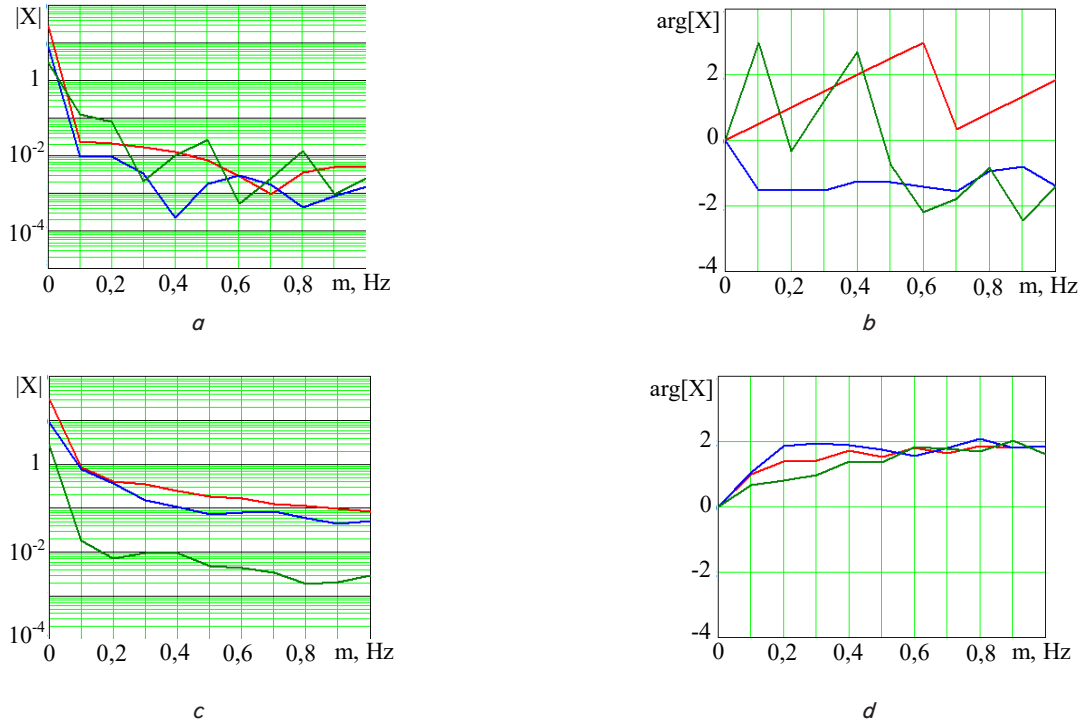
Fig. 2. Amplitude and phase spectra for the studied parameters of the gas medium in the chamber before and after the ignition of paper: *a* — amplitude spectrum in the absence of ignition; *b* — phase spectrum in the absence of ignition; *c* — amplitude spectrum during ignition; *d* — phase spectrum during ignition
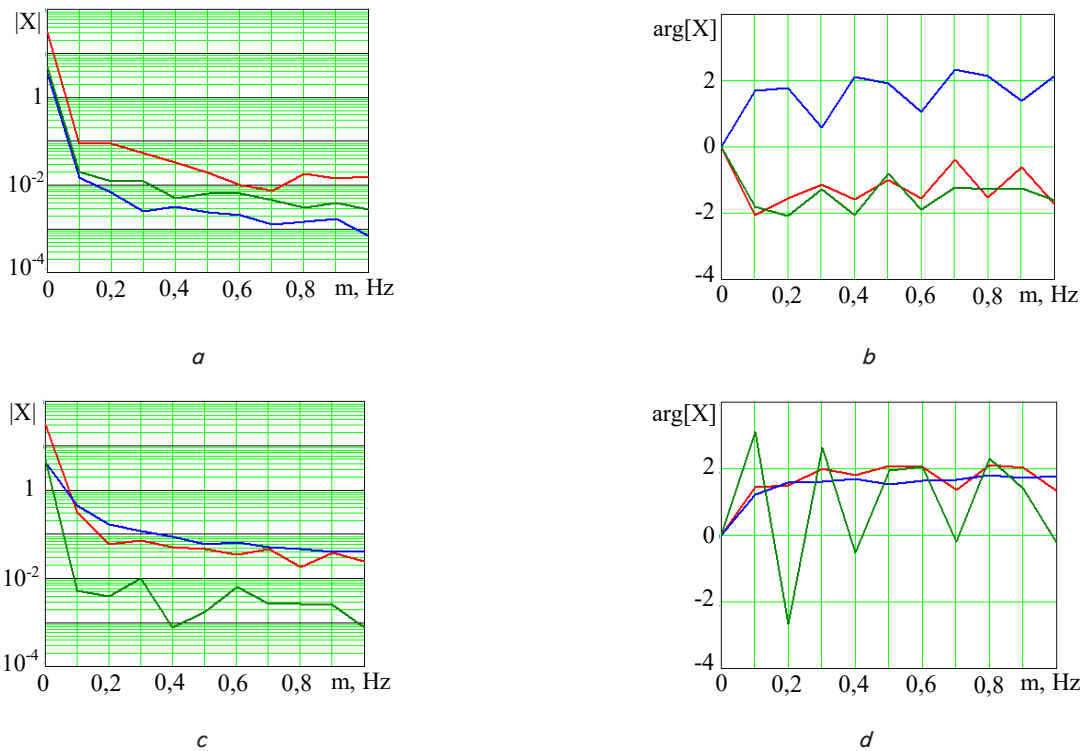

Fig. 3. Amplitude and phase spectra for the studied parameters of the gas medium in the chamber before and after wood ignition: *a* — amplitude spectrum in the absence of ignition; *b* — phase spectrum in the absence of ignition; *c* — amplitude spectrum during ignition; *d* — phase spectrum during ignition

Similar amplitude and phase spectra for the mean volume temperature, CO concentration, and smoke density of the chamber's GM before and after the ignition of textiles are shown in Fig. 4.
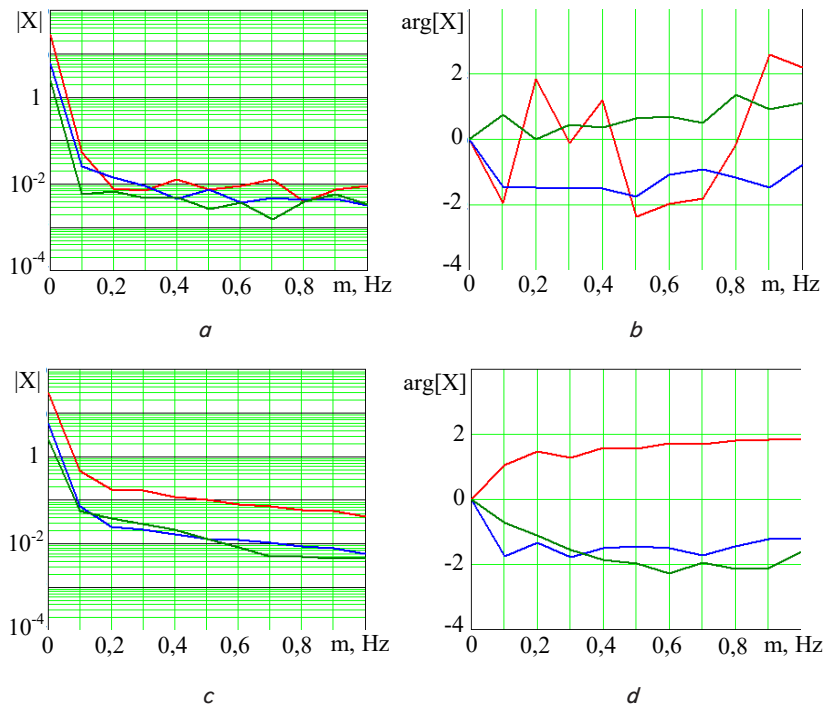
Fig. 4. Amplitude and phase spectra for the studied parameters of the gas medium in the chamber before and after ignition of textiles: *a* — amplitude spectrum in the absence of ignition; *b* — phase spectrum in the absence of ignition; *c* — amplitude spectrum during ignition; *d* — phase spectrum during ignition

In Fig. 1–4, for the specified study intervals, the amplitude and phase spectra of the dynamics of the average volumetric temperature are indicated in red, the dynamics of the concentration of CO are indicated in blue, and the dynamics of the smoke density of GM in the experimental chamber are indicated in green.

6. Discussion of results of studying the spectral features of the gaseous medium during the ignition of materials

It follows from the analysis of data in Fig. 1–4 that the amplitude spectra of the dynamics of the studied hazardous parameters of GM in the chamber are uninformative from the point of view of detecting fires and warning of fire in the room. This is explained by the similarity of spectra. Amplitude spectra indicate the predominance of low-frequency components in them, including the component with zero frequency. For example, the main contribution to the amplitude spectrum of the dynamics of the studied hazardous GM parameters in the chamber, following the results obtained, is made by the frequency components of the range 0–0.2 Hz. At the same time, the amplitude of frequency components over 0.2 Hz decreases with increasing frequency. Phase spectra of dynamics of hazardous GM parameters are more informative from the point of view of detecting fires and are sensitive to fires. For example, the phase distribution for frequency components up to 1 Hz in the absence of ignition is heterogeneous. The heterogeneity of the phase values of the frequency components for the dynamics of the studied hazardous GM parameters, in this case, is random and can vary from $-130°$ to $+130°$. At the same time, in the case of ignition of the material, the random phase dispersion for the frequency components of the dynamics of the studied hazardous GM parameters is significantly reduced (Fig. 2, *d*). For example, when alcohol is ignited, the random phase variation of the frequency components is significantly reduced for the dynamics of the mean volumetric temperature and the concentration of CO (Fig. 1, *d*). However, for smoke density, the random phase dispersion remains significant. A similar situation is observed in the case of wood fire (Fig. 3, *d*). For the ignition of textiles, the random spread of phases of frequency components is significantly reduced for all studied GM parameters (Fig. 4, *d*). However, the sign of the maximum values of the phases of the frequency components is different and depends on the studied GM hazard parameter. For example, for the dynamics of the average volume temperature, the sign of the maximum phase values is positive, and for the dynamics of the CO concentration and smoke density – negative.

Thus, the results of our experimental studies indicate that the nature of the random phase dispersion of the frequency components of the dynamics of hazardous GM parameters depends on the type of ignition material. This means that by the nature of the unevenness of the phase spectrum of the dynamics of hazardous GM parameters, in principle, it is possible not only to detect fires in the premises but also to recognize the type of ignition material. However, it should be noted that the use of the spectral approach in question does not make it possible to obtain information about the time of appearance of specific frequency components of the spectrum (their amplitudes and phases). Therefore, the spectral approach does not provide temporary localization of fires, which is an important indicator for fire prevention. In this case, the ignition time in this approach is determined only by the time position of the data sampling interval for the corresponding hazardous GM parameter. In addition, the accuracy of calculating the amplitude and phase spectra depends on the size of this sample. At the same time, the larger the sample size of the data, the more accurately the specified instantaneous spectra are calculated. For example, in the experiment, the sample size was determined by 100 counts followed by an interval of 0.1 s. This means that the analysis interval in the experiment was 10 s. Therefore, the results obtained from the study of the spectral features of the dynamics of hazardous GM parameters make it possible to detect a change in the spectral composition of the dynamics only for fixed intervals of data sampling time. In the experiment, this interval was 10 s. Therefore, for this interval, the frequency resolution corresponds to a value of 0.1 Hz.

The merit of this study is in the novelty and originality of the results associated with the spectral features of the dynamics of hazardous GM parameters and the possibility of their use for early detection of fires and warning of FP.

The limitations of the study include the fact that the results obtained are based on the experimental measurements of hazardous GM parameters in a laboratory chamber. In this regard, verification of our results requires additional fire tests, taking into consideration combustible materials characteristic of the real facilities.

7. Conclusions

1. A theoretical substantiation of the ongoing studies of the spectral features of the dynamics of the main hazardous parameters of the gas medium during the ignition of materials has been carried out. The basic approach, in this case, is to calculate the direct discrete Fourier transform for the same number of discrete measurements of the time intervals of the studied dynamics of the hazardous parameters of the gas medium before and after the ignition of the material. With this approach, the discrete Fourier transform makes it possible to determine the instantaneous amplitude and instantaneous phase spectra for the time intervals under consideration. This makes it possible to study the features of the distribution of instantaneous amplitudes and phases of harmonic components in the spectrum of dynamics of hazardous parameters of the gas medium before and after the ignition of materials.

2. The amplitude and phase spectra of the dynamics of the main hazardous factors of the gas medium during the ignition of test materials in the laboratory chamber have been investigated. The results of experimental studies indicate that the nature of the amplitude spectrum is uninformative from the point of view of detecting fires and is not sensitive enough to fires. This is explained by the similarity of amplitude spectra. Amplitude spectra are characterized by the predominance of low-frequency components in them, including the frequency component with zero frequency. It has been established that the main contribution to the amplitude spectrum of the dynamics of the studied dangerous parameters of the gas medium in the chamber is made by the frequency components of the range 0–0.2 Hz. At the same time, the contribution to the amplitude spectrum of frequency components over 0.2 Hz decreases significantly with increasing frequency. Phase spectra of dynamics of hazardous parameters of the gas medium for high-frequency components are more informative and sensitive from the point of view of detecting fires. It has been established that for the phase spectrum, the nature of the random phase dispersion for frequency components exceeding 0.2 Hz is informative. In this case, the nature of the phase dispersion for these frequency components in the spectrum depends on the type of ignition material. It is shown that by the nature of the distribution of phases of the frequency components of the spectrum of dynamics of hazardous parameters of the gas medium, it is possible not only to detect fires in the early stages and warn of a fire in the premises but also to recognize the type of ignition material. However, the results of our studies show that the phase spectrum of dynamics of hazardous parameters of the gas medium during fires does not allow for accurate localization at the time of the onset of fires. The temporal localization of ignition is determined by the current temporal position of the strobe of the sample of measurements used to determine the instantaneous spectrum of the dynamics of the dangerous parameter of the gaseous medium. It is noted that the accuracy of calculating the amplitude and phase spectra depends on the sample size of the measurements.

References

1. Vambol, S., Vambol, V., Bogdanov, I., Suchikova, Y., Rashkevich, N. (2017). Research of the influence of decomposition of wastes of polymers with nano inclusions on the atmosphere. Eastern-European Journal of Enterprise Technologies, 6 (10 (90)), 57–64. doi: https://doi.org/10.15587/1729-4061.2017.118213

2. Tan, P., Steinbach, M., Kumar, V. (2005). Introduction to Data Mining. Addison Wesley, 864.

3. Semko, A. N., Beskrovnaya, M. V., Vinogradov, S. A., Hritsina, I. N., Yagudina, N. I. (2014). The usage of high speed impulse liquid jets for putting out gas blowouts. Journal of Theoretical and Applied Mechanics, 52 (3), 655–664.

4. Andronov, V., Pospelov, B., Rybka, E., Skliarov, S. (2017). Examining the learning fire detectors under real conditions of application. Eastern-European Journal of Enterprise Technologies, 3 (9 (87)), 53–59. doi: https://doi.org/10.15587/1729-4061.2017.101985

5. Migalenko, K., Nuianzin, V., Zemlianskyi, A., Dominik, A., Pozdieiev, S. (2018). Development of the technique for restricting the propagation of fire in natural peat ecosystems. Eastern-European Journal of Enterprise Technologies, 1 (10 (91)), 31–37. doi: https://doi.org/10.15587/1729-4061.2018.121727

6. Vambol, S., Vambol, V., Sobyna, V., Koloskov, V., Poberezhna, L. (2019). Investigation of the energy efficiency of waste utilization technology, with considering the use of low-temperature separation of the resulting gas mixtures. Energetika, 64 (4). doi: https://doi.org/10.6001/energetika.v64i4.3893

7. Dubinin, D., Korytchenko, K., Lisnyak, A., Hrytsyna, I., Trigub, V. (2018). Improving the installation for fire extinguishing with finely¬dispersed water. Eastern-European Journal of Enterprise Technologies, 2 (10 (92)), 38–43. doi: https://doi.org/10.15587/1729-4061.2018.127865

8. Kovalov, A., Otrosh, Y., Ostroverkh, O., Hrushovinchuk, O., Savchenko, O. (2018). Fire resistance evaluation of reinforced concrete floors with fire-retardant coating by calculation and experimental method. E3S Web of Conferences, 60, 00003. doi: https://doi.org/10.1051/e3sconf/20186000003

9. Reproduced with permission from fire loss in the United States during 2019 (2020). National Fire Protection Association.

10. Otrosh, Y., Semkiv, O., Rybka, E., Kovalov, A. (2019). About need of calculations for the steel framework building in temperature influences conditions. IOP Conference Series: Materials Science and Engineering, 708 (1), 012065. doi: https://doi.org/10.1088/1757-899x/708/1/012065

11. Dadashov, I., Loboichenko, V., Kireev, A. (2018). Analysis of the ecological characteristics of environment friendly fire fighting chemicals used in extinguishing oil products. Pollution Research, 37 (1), 63–77.

12. Kustov, M. V., Kalugin, V. D., Tutunik, V. V., Tarakhno, E. V. (2019). Physicochemical principles of the technology of modified pyrotechnic compositions to reduce the chemical pollution of the atmosphere. Voprosy Khimii i Khimicheskoi Tekhnologii, 1, 92–99. doi: https://doi.org/10.32434/0321-4095-2019-122-1-92-99

13. Pospelov, B., Andronov, V., Rybka, E., Krainiukov, O., Maksymenko, N., Meleshchenko, R. et. al. (2020). Mathematical model of determining a risk to the human health along with the detection of hazardous states of urban atmosphere pollution based on measuring the current concentrations of pollutants. Eastern-European Journal of Enterprise Technologies, 4 (10 (106)), 37–44. doi: https://doi.org/10.15587/1729-4061.2020.210059

14. Sadkovyi, V., Andronov, V., Semkiv, O., Kovalov, A., Rybka, E., Otrosh, Yu. et. al.; Sadkovyi, V., Rybka, E., Otrosh, Yu. (Eds.) (2021). Fire resistance of reinforced concrete and steel structures. Kharkiv: PC TECHNOLOGY CENTER, 180. doi: https://doi.org/10.15587/978-617-7319-43-5

15. Pospelov, B., Andronov, V., Rybka, E., Samoilov, M., Krainiukov, O., Biryukov, I. et. al. (2021). Development of the method of operational forecasting of fire in the premises of objects under real conditions. Eastern-European Journal of Enterprise Technologies, 2 (10 (110)), 43–50. doi: https://doi.org/10.15587/1729-4061.2021.226692

16. Andronov, V., Pospelov, B., Rybka, E. (2017). Development of a method to improve the performance speed of maximal fire detectors. Eastern-European Journal of Enterprise Technologies, 2 (9 (86)), 32–37. doi: https://doi.org/10.15587/1729-4061.2017.96694

17. Pospelov, B., Andronov, V., Rybka, E., Skliarov, S. (2017). Design of fire detectors capable of self-adjusting by ignition. Eastern-European Journal of Enterprise Technologies, 4 (9 (88)), 53–59. doi: https://doi.org/10.15587/1729-4061.2017.108448

18. Pospelov, B., Andronov, V., Rybka, E., Skliarov, S. (2017). Research into dynamics of setting the threshold and a probability of ignition detection by self-adjusting fire detectors. Eastern-European Journal of Enterprise Technologies, 5 (9 (89)), 43–48. doi: https://doi.org/10.15587/1729-4061.2017.110092

19. Cheng, C., Sun, F., Zhou, X. (2011). One fire detection method using neural networks. Tsinghua Science and Technology, 16 (1), 31–35. doi: https://doi.org/10.1016/s1007-0214(11)70005-0

20. Ding, Q., Peng, Z., Liu, T., Tong, Q. (2014). Multi-Sensor Building Fire Alarm System with Information Fusion Technology Based on D-S Evidence Theory. Algorithms, 7 (4), 523–537. doi: https://doi.org/10.3390/a7040523

21. BS EN 54-30:2015. Fire detection and fire alarm systems. Multi-sensor fire detectors. Point detectors using a combination of carbon monoxide and heat sensors. doi: https://doi.org/10.3403/30266860

22. BS EN 54-31:2014. Fire detection and fire alarm system. Multi-sensor fire detectors. Point detectors using a combination of smoke, carbon monoxide and optionally heat sensors. doi: https://doi.org/10.3403/30256418u

23. ISO 7240-8:2014. Fire detection and alarm systems. Point-type fire detectors using a carbon monoxide sensor in combination with a heat sensor. doi: https://doi.org/10.3403/30280584

24. Aspey, R. A., Brazier, K. J., Spencer, J. W. (2005). Multiwavelength sensing of smoke using a polychromatic LED: Mie extinction characterization using HLS analysis. IEEE Sensors Journal, 5 (5), 1050–1056. doi: https://doi.org/10.1109/jsen.2005.845207

25. Chen, S.-J., Hovde, D. C., Peterson, K. A., Marshall, A. W. (2007). Fire detection using smoke and gas sensors. Fire Safety Journal, 42 (8), 507–515. doi: https://doi.org/10.1016/j.firesaf.2007.01.006

26. Shi, M., Bermak, A., Chandrasekaran, S., Amira, A., Brahim-Belhouari, S. (2008). A Committee Machine Gas Identification System Based on Dynamically Reconfigurable FPGA. IEEE Sensors Journal, 8 (4), 403–414. doi: https://doi.org/10.1109/jsen.2008.917124

27. Skinner, A. J., Lambert, M. F. (2006). Using Smart Sensor Strings for Continuous Monitoring of Temperature Stratification in Large Water Bodies. IEEE Sensors Journal, 6 (6), 1473–1481. doi: https://doi.org/10.1109/jsen.2006.881373

28. Cheon, J., Lee, J., Lee, I., Chae, Y., Yoo, Y., Han, G. (2009). A Single-Chip CMOS Smoke and Temperature Sensor for an Intelligent Fire Detector. IEEE Sensors Journal, 9 (8), 914–921. doi: https://doi.org/10.1109/jsen.2009.2024703

29. Wu, Y., Harada, T. (2004). Study on the Burning Behaviour of Plantation Wood. Scientia Silvae Sinicae, 40, 131.

30. Zhang, D., Xue, W. (2010). Effect of Heat Radiation on Combustion Heat Release Rate of Larch. Journal of West China Forestry Science, 39, 148.

31. Ji, J., Yang, L., Fan, W. (2003). Experimental Study on Effects of Burning Behaviours of Materials Caused by External Heat Radiation. Journal of Combustion Science and Technology, 9, 139.

32. Peng, X., Liu, S., Lu, G. (2005). Experimental Analysis on Heat Release Rate of Materials. Journal of Chongqing University, 28, 122.

33. Pospelov, B., Andronov, V., Rybka, E., Meleshchenko, R., Gornostal, S. (2018). Analysis of correlation dimensionality of the state of a gas medium at early ignition of materials. Eastern-European Journal of Enterprise Technologies, 5 (10 (95)), 25–30. doi: https://doi.org/10.15587/1729-4061.2018.142995

34. Pospelov, B., Andronov, V., Rybka, E., Meleshchenko, R., Borodych, P. (2018). Studying the recurrent diagrams of carbon monoxide concentration at early ignitions in premises. Eastern-European Journal of Enterprise Technologies, 3 (9 (93)), 34–40. doi: https://doi.org/10.15587/1729-4061.2018.133127

35. Pospelov, B., Rybka, E., Meleshchenko, R., Krainiukov, O., Biryukov, I., Butenko, T. et. al. (2021). Short-term fire forecast based on air state gain recurrence and zero-order brown model. Eastern-European Journal of Enterprise Technologies, 3 (10 (111)), 27–33. doi: https://doi.org/10.15587/1729-4061.2021.233606

36. Pospelov, B., Rybka, E., Togobytska, V., Meleshchenko, R., Danchenko, Y., Butenko, T. et. al. (2019). Construction of the method for semi-adaptive threshold scaling transformation when computing recurrent plots. Eastern-European Journal of Enterprise Technologies, 4 (10 (100)), 22–29. doi: https://doi.org/10.15587/1729-4061.2019.176579

37. McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C., Overholt, K. (2016). Fire Dynamics Simulator Technical Reference Guide. Vol. 3. National Institute of Standards and Technology.

38. Floyd, J., Forney, G., Hostikka, S., Korhonen, T., McDermott, R., McGrattan, K. (2013). Fire Dynamics Simulator. User's Guide. V. 6. National Institute of Standard and Technology.

39. Polstiankin, R. M., Pospelov, B. B. (2015). Stochastic models of hazardous factors and parameters of a fire in the premises. Problemy pozharnoy bezopasnosti, 38, 130–135.

40. Heskestad, G., Newman, J. S. (1992). Fire detection using cross-correlations of sensor signals. Fire Safety Journal, 18 (4), 355–374. doi: https://doi.org/10.1016/0379-7112(92)90024-7

41. Gottuk, D. T., Wright, M. T., Wong, J. T., Pham, H. V., Rose-Pehrsson, S. L., Hart, S. et. al. (2002). Prototype Early Warning Fire Detection Systems: Test Series 4 Results. NRL/MR/6180-02-8602. Naval Research Laboratory.

42. Pospelov, B., Rybka, E., Meleshchenko, R., Gornostal, S., Shcherbak, S. (2017). Results of experimental research into correlations between hazardous factors of ignition of materials in premises. Eastern-European Journal of Enterprise Technologies, 6 (10 (90)), 50–56. doi: https://doi.org/10.15587/1729-4061.2017.117789