Розроблено метод оперативного частотно-часового подання флуктуацій параметрів газового середовища на ранній стадії пожежі в приміщеннях. Теоретична база методу базується на передачі порушень рівноважного стану газовим середовищем у зону чутливих сенсорів, при цьому осередок займання розглядається у вигляді рухомого джерела збурень параметрів. Відмінними рисами методу є порівняльна простота та використання даних в поточному часі

Ключові слова: осередок займання, газове середовище, рівноважний стан, частотно-часове подання, пожежні сенсорі

Разработан метод оперативного частотно-временного представления флуктуаций параметров газовой среды на ранней стадии пожара в помещениях. Теоретическая база метода базируется на передаче нарушений равновесного состояния газовой средой в зону чувствительных сенсоров, при этом очаг возгорания рассматривается как движущийся источник возмущений. Отличительными особенностями метода являются сравнительная простота и использование данных в текущем времени

Ключевые слова: очаг возгорания, газовая среда, равновесное состояние, частотно-временное представление, пожарные сенсоры

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DEVELOPMENT OF THE METHOD OF FREQUENCY-TEMPORAL REPRESENTATION OF FLUCTUATIONS OF GASEOUS MEDIUM PARAMETERS AT FIRE

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1. Introduction

World statistics shows that considerable part of fires occurs at premises. In this case, the number of fatalities at such fires is more than 80 % of the total. That is why one of the world's main and priority problems is to prevent ignitions and fires at premises. It is known that the solution to this problem involves safe and timely identification of ignitions when it is relatively easy to eliminate ignition and prevent the development of a large-scale fire. However, the initial stage of a fire is characterized by a diversity of actual processes and minor changes in dangerous factors of gaseous medium at premises, making early fire detection difficult. That is why the development of new methods of representation and analysis of hazardous factors of an early ignition at premises is a relevant task.

2. Literature review and problem statement

Paper [1] reports experimental study of the processes of starting a fire at premises. The results of studying the processes of combustion of materials under external thermal influence are presented in articles [2, 3]. Experimental analysis of the rate of heat release of combustible materials in case of a fire is carried out in [4]. In papers [1–4], it was noted that the processes of fire development at premises in general have undefined and essentially non-stationary nature. In this case, the studies are limited to temporal dynamics of basic parameters of the gaseous medium. Studies [5, 6] focus on the development of temporal methods for representing and determining the temperature of the gaseous medium at premises in case of a fire. Papers [7, 8] explore fire sensors that are self-tuning in time. However, these papers are limited to temporal unpredictability and non-stationary changes in hazardous factors of the gaseous medium in time. In this case, fluctuations of hazardous factors of the gaseous medium are not considered. Article [9] explores temporal autocorrelations and paired correlations of hazardous factors of the gaseous medium in the region of a near- ceiling jet, simulated in a special chamber. However, correlations of fluctuations of dynamics of hazardous factors of the gaseous medium, which are essential for detection of early ignitions, are not studied. The methods of frequency-temporal representation of these fluctuations are not considered. In this case, known statistical representations of hazardous factors of the gaseous medium, applied for stationary processes, are currently used for fire detection at premises [10, 11]. It is known that the statistical approach to representation of autocorrelations and the energy spectrum in stationary approximation yields only an averaged idea of energy distribution on lags and frequencies. Such views do not take into account the phase structure of processes. In this regard, it is necessary to use modern frequency-temporal representations, specifically the methods of frequency-temporal distribution, for analysis of a subtle structure of early ignition factors at premises [12, 13]. The research into dynamics of major actual [14, 15] and model hazardous fires [9] indicate that ignitions violate equilibrium state of the gaseous medium in premises. Ignitions also result in random fluctuations of the basic parameters of the gaseous medium, localized in space and time.

Due to the local nature of fluctuations, the use of well-known statistical methods of frequency-temporal representation in practice turns out to be quite limited. The methods of frequency-temporal representation [16], based on the concepts of current and instantaneous spectrum [17, 18], should be considered more constructive. Among a number of such representations, the Wigner distribution [19, 20] plays an important role in theory and practice of analysis of non-stationary processes. This distribution has some properties that make it a unique tool for studying the frequency-temporal structure of various non-stationary processes [21, 22]. However, despite the known merits, a certain complexity of this distribution makes it difficult to use it directly for frequency-temporal representation of hazardous factors of the gaseous medium at earlier ignitions. That is why provision of operative frequency-temporal representation of fluctuations of parameters of gaseous medium for detection of fires at premises at an early stage is a relevant and unresolved part of the problem.

3. The aim and objectives of the study

The aim of present research is to study frequency-temporal representation of fluctuations of hazardous factors of the gaseous medium, which are recorded in real time by the appropriate fire sensors.

To accomplish the aim, the following tasks were set:

– to state basic assumptions about the features of dynamics of gaseous medium parameters at an early ignition of materials in premises;

– to substantiate the theoretical basis for development of the method of frequency-temporal representation of the major hazardous factors of the gaseous medium;

– to devise the method of frequency-temporal representation of fluctuations of the major hazardous factors of gaseous medium in real time of observation;

– to verify the method on the basis of experimental data of registration of gaseous medium parameters at an early ignition of alcohol, paper, wood and textiles in a simulation chamber.

4. Basic assumptions about the features of dynamics of gaseous medium parameters in case of a fire

It is common to regard temperature of gaseous medium and concentration of products of ignition of fire load materials as hazardous factors of gaseous medium in premises. At early ignition, they usually include concentrations of smoke and carbon monoxide. Following the results of the experimental [14, 15] and experimental-computational studies [9, 23], it is possible to state a number of assumptions about the features of dynamics of the registered hazardous factors of gaseous medium at an early ignition of materials at premises.

Assumption 1. In the absence of an ignition, hazardous factors of gaseous medium at premises correspond to its equilibrium state [9]. Dynamics of hazardous factors in this state is mainly determined by the chaotic motion of molecules and particles of the gaseous medium. In this case, the dynamics is characterized by current average and fluctuations of the corresponding parameters of gaseous medium. By virtue of the chaotic nature of motion of molecules and particles of gaseous medium, fluctuations are mostly stationary and weakly correlated random processes.

Assumption 2. Occurrence of ignitions leads to disruption of the equilibrium state of the gaseous medium. The moment when an ignition occurs is random. Violation of the equilibrium state is accompanied by fluctuations of parameters of gaseous medium. Gaseous medium of premises as a macrosystem, in this case tries to deter a disruption of its equilibrium state. That is why mean values of parameters of gaseous medium change little and are not quite informative for early detection of ignition in premises. In this case, ignition-induced fluctuations of parameters are translated by the gaseous medium to the area of location of fire sensors (of temperature, concentration of smoke and carbon monoxide).

Assumption 3. For early detection of ignitions in premises, it is possible to use the information, contained in fluctuations of gaseous medium parameters, registered by correspondent fire sensors. These fluctuations contain information about the time and the rate of process of disruption of equilibrium state of the gaseous medium.

Assumption 4. Actual fluctuations of gaseous medium parameters during ignitions are non-stationary processes, the study of which does not fit in the methodology for representation of stationary processes. That is why it is necessary to develop special methods for representation of fluctuations of gaseous medium parameters at an early ignition of materials in premises. In this case, fluctuations of parameters at an initial stage of ignition have a complex local non-stationary in time nature. This means that for representation of fluctuations, it is necessary to consider their temporal and spectral characteristics.

5. Theoretical basis for the development of a method of frequency-temporal fluctuations of gaseous medium parameters

In the general case, if there is a violation of the equilibrium state of gaseous medium, its parameters will be characterized by non-stationary current average deviations. The parameters, registered by the sensors, are a response of the gaseous medium to disturbances, caused by an early hotbed of a fire. In this case, the hotbed of fire is a moving source of disturbances, which may occur at random moments and at any arbitrary point of premises. This means that registered data about the state of gaseous medium will carry information about temporal and frequency shifts of its parameters.

That is why we will assume that registered data x about an arbitrary parameter of hazardous factors of gaseous medium at an early ignition have a temporal and a frequency shifts at the same time. Let operator T_τ describe a temporal data shift by value τ, and operator T_φ – their frequency shift by value φ. Then for data x,

$$T_\phi \circ T_\tau \circ x = T_\tau \circ T_\phi \circ x$$

will hold.

In this case, the standard deviation between x and $T_\varphi \circ T_\tau \circ x$ will be determined by magnitude

$$\varepsilon^2 = \| x \|^2 + \| T_\varphi \circ T_\tau \circ x \|^2 - 2\langle x, T_\phi \circ T_\tau \circ x \rangle,$$

where $\|x\|^2$ represents energy E_x of registered data x. If temporal τ and frequency φ shifts are small, $\|x\|^2+\|T_\varphi \circ T_\tau \circ x\|^2=E_x$. Hence, we will obtain that magnitude

$$\varepsilon^2 = 2E_x - 2\langle x, T_\phi \circ T_\tau \circ x \rangle.$$

Scalar product $2\langle x, T_\phi \circ T_\tau \circ x \rangle$ in this expression will determine the known uncertainty function

$$\chi_{xx}(\tau, \varphi) = \langle x, T_\phi \circ T_\tau \circ x \rangle.$$

In case of continuous data x(t) and temporal consideration, uncertainty function

$$\chi_{xx}(\tau,\phi) = \int_{-\infty}^{\infty} x(t)x(t-\tau)e^{j2\pi\phi t}\mathrm{d}t. \quad (1)$$

From expression (1) it follows that $\chi_{xx}(\tau, 0)=C_{xx}(\tau)$, and $\chi_{xx}(0, \varphi)=\Gamma_{xx}(\varphi)$, where $C_{xx}(\tau)$ and $\Gamma_{xx}(\varphi)$ represent respectively the data correlation functions in temporal and frequency regions. Function $\Gamma_{xx}(\varphi)$, unlike $C_{xx}(\tau)$, characterizes correlation between frequency components in data spectrum. Therefore, consideration of uncertainty function for the registered data generalizes the concept of correlation function for the data in case of their shift by time and frequency. Uncertainty function (1) has a number of useful properties. For example, the value of uncertainty function at origin $\chi_{xx}(0, 0)=E_x$ is maximum and equal to energy of the observed data. It is also known that two-dimensional Fourier transformation of uncertainty function $TF[\chi_{xx}(\tau, \varphi)]=$ $=K_{xx}(f, t)$, where f and t characterize the values of frequency and time for data $x(t)$. In this case, function $K_{xx}(f, t)=$ $=x(t)X^*(f)e^{-j2\pi ft}$ determines instantaneous spectrum or frequency-temporal energy density for considered data $x(t)$ on the plain in coordinates of time t and frequency f, where $X^*(f)$ is the complex conjugate Fourier transformation of $x(t)$. It can be shown that squared modulus of uncertainty function is an invariant with respect to the double Fourier transformation

$$|\chi_{xx}(\tau,\phi)|^2 \frac{\tau f}{\phi t} |K_{xx}(f,t)|^2. \quad (2)$$

Property (2) indicates a new approach to determining squared modulus of instant spectrum or squared modulus of frequency-temporal energy density for arbitrary data $x(t)$ in plane (t,f) of uncertainty function. That is why the proposed approach is based on a chain (2) of transformations from squared modulus of uncertainty function to squared modulus of frequency-temporal energy density.

6. Development of the method of frequency-temporal representation of fluctuations of gaseous medium parameters

The object of research is fluctuations of parameters of gaseous medium, characterizing violation of its equilibrium state at early occurrence of ignitions. In this regard, it is necessary to develop an appropriate method for their frequency-temporal representation. In this case, one of the important implementation requirements is the possibility of operation of the method in real time.

We will assume that the registered parameters of gaseous medium on the observation interval represent implementations of complex of non-stationary processes. Usually, the left boundary of the data registration interval is fixed and determined by the initial moment of observation. In this case, the right boundary of the interval is not fixed and is determined by current time of data registration. Let an arbitrary parameter of the state of gaseous medium be registered at discrete moments j with a small pitch of Δt seconds. For convenience of further consideration, moments j will be enumerated from 0 (beginning of data registration) to T_j, where T_j determines a discrete moment, corresponding to current time T of data registration by the given sensor. During discrete data registration, in order to determine current fluctuations, the observed parameters $x(t)$ of the gaseous medium on the interval of observation $[0, T]$ will be transformed into current increments $y_j=x_{j+1}-x_j$ for discrete moments $j=0, 1,..., T_j$. The values of the observed parameter x_{j+1} and x_j correspond to discrete moments, characterized by a small pitch of discreteness Δt. That is why it is possible to argue that at early ignition their mean values will differ slightly. This means that magnitude $y_j=x_{j+1}-x_j$ will determine current increment of the correspondent parameter at moment j. Due to the random character of the state of gaseous medium, increments $y_j=x_{j+1}-x_j$ will determine current fluctuations of the parameter, caused by violation of equilibrium state of gaseous medium by the hot bed of ignition.

The proposed method is based on application of the ratio (2) to the data, obtained before a specified discrete moment k. For k, current frequency-temporal representation $TF_y(j,f,k)$ of fluctuations y_j for moment $i=j$, following (2), will be determined by the expression

$$TF_y(j,f,k) = = if\left\{ j<k, 0, \sum_{a=0}^{k-1} y_j y_{j-a} \exp\{2i\pi a f / k\} \right\}, \quad (3)$$

where a is the summation variable; j, f are the discrete values of time and frequency. Magnitude k in (3) determines the volume of temporal sample of data, used for operative frequency-temporal representation of fluctuations at moment $j=k$ of observation time. In this case, magnitude k will determine the widow size at operative frequency-temporal representation of fluctuations at subsequent moments $j>k$ of data registration time. It should be noted that the method (3) makes it possible to estimate frequency-temporal representation of fluctuations of parameters of gaseous medium based on registration of current data, obtained by correspondent sensors in premises. In this case, (3) uses a rectangular window, the width k of which can be selected based on the requirements for frequency-temporal representation of fluctuations, determined by the problem solved. That is why (3) has all the known advantages and disadvantages of the rectangular transformation window. For subsequent smoothing of current estimations (3) and obtaining correspondent smoothed frequency-temporal representation (*TFD* –time frequency distribution), it is proposed to use the current average operator, such as implementation of transformation of the following form

$$TFD(j,f,wcp,k)= \\ =if\left\{j<w, TF_y(j,f,k), \sum_{r=0}^{k-1}\frac{TF_y(j-r,f,k)}{w}\right\}, \qquad (4)$$

where *r* is the summation variable; *w* is the width of the window of current average operator. The expression (4) determines development of the method (3) of smoothed operative estimation of discrete frequency-temporal representation of fluctuations of gaseous medium parameters at premises based on application of the current average operator to current representation $TF_y(j, f, k)$. If modular values of frequency-temporal representations are of most interest for applications, correspondent representations $|TF_y(j, f, k)|$ и $|TFD(j, f, w, k)|$ can be determined based on expressions (3) and (4).

Thus, ratios (3) and (4) determine the proposed methods of current and current smoothed estimation of discrete frequency-temporal representation of fluctuations of gaseous medium parameters, registered by correspondent sensors in premises.

7. Verification of the method of frequency-temporal fluctuations of gaseous medium parameters

Verification of the method was carried out based of the experimental data of registration of non-stationary fluctuations of gaseous medium parameters in a simulation chamber at ignition of combustible materials in the form of alcohol, paper, wood and textiles [24]. Fig. 1 shows the results of operative frequency-temporal fluctuations of gaseous medium temperature in the chamber at ignition of correspondent materials. In coordinates: discrete counting t by time, discrete count *f* by frequency.

In order to verify the proposed method for different parameters of gaseous medium, the chamber was naturally ventilated for 5–7 minutes between each ignition of tested materials. Similar results of frequency-temporal representation for fluctuations of concentrations of carbon monoxide and smoke in the gaseous medium of the chamber at ignition of test materials are shown, respectively, in Fig. 2, 3. It should be noted that the results in Fig. 1–3 are obtained at frequency resolution of 0.05 Hz, window width of *k*=10 counts for current estimation of representations and window width w of smoothing operator that is equal to 20 counts.

The results in Fig. 1–3 are obtained based on actual measurement errors in the chamber, as well as errors of data digitization. In this case, digitization errors are negligible compared to measurement errors. That is why within a methodological error of the proposed method, the obtained frequency-temporal representations allow making a reliable assessment of their differences for the studied combustible materials taking into consideration sensory measurement errors. It should be noted that the used sensors are applied in actual fire detectors. That is why the obtained frequency-temporal representations correspond to ignitions in the chamber, taking into account measurement errors. This indicates adequacy of representation to actual conditions of the experiment and reliability of the results of verification of the proposed method.

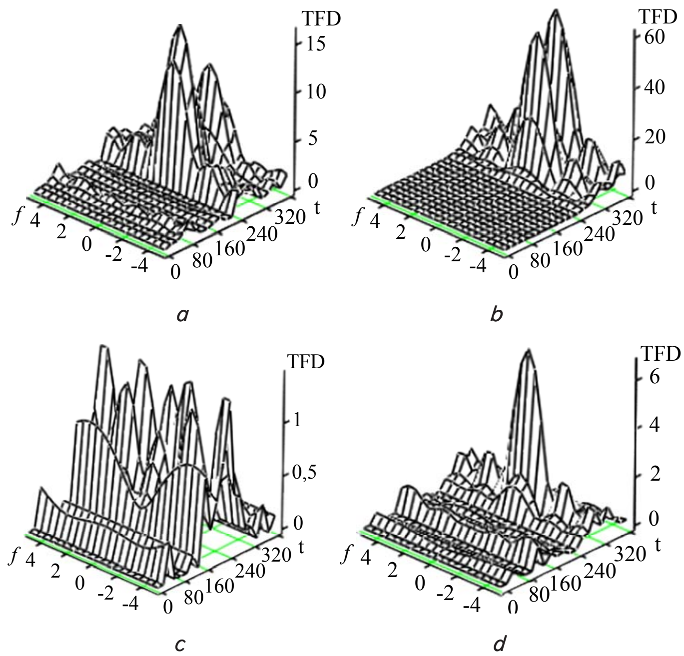

Fig 1. Frequency-temporal representation of fluctuations of gaseous medium temperature in the chamber:
a — alcohol; *b* — paper; *c* — wood; d — textiles

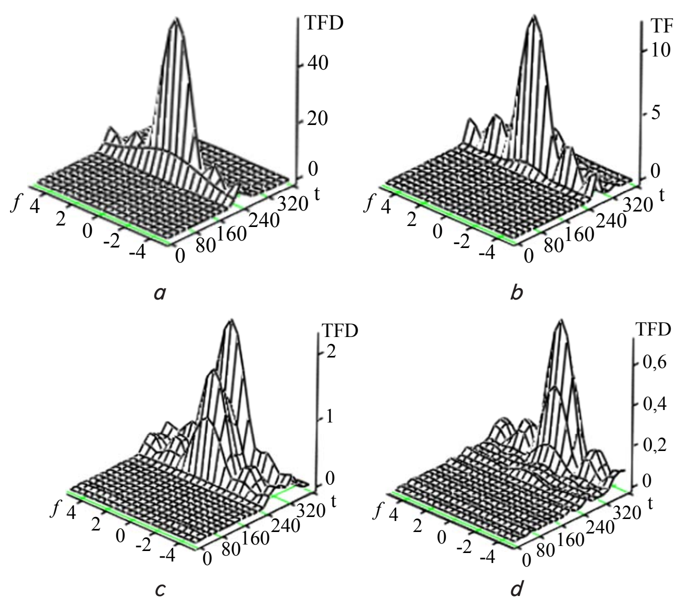

Fig. 2. Frequency-temporal representation of fluctuations of carbon monoxide concentration in gaseous medium in the chamber: *a* — alcohol; *b* — paper; *c* — wood; d — textiles

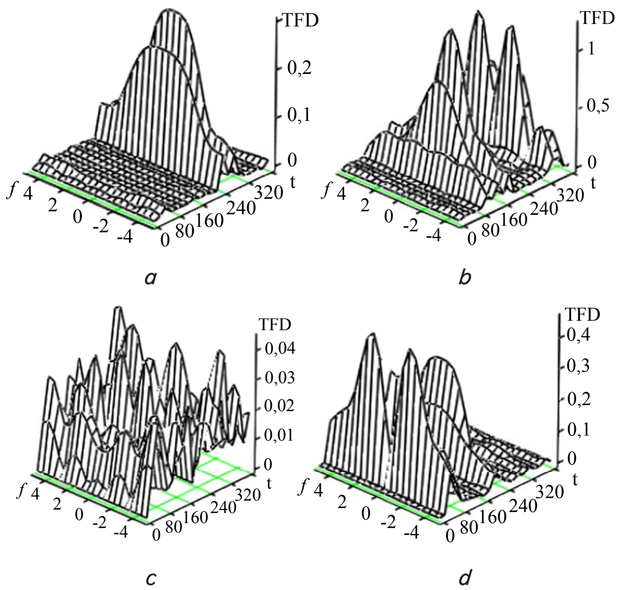

Fig. 3. Frequency-temporal representation of smoke concentration fluctuations in a gaseous medium of the chamber at ignitions: *a* — alcohol; *b* — paper; *c* — wood; d —textiles

8. Discussion of results of development of the method of frequency-temporal representations of fluctuations of gaseous medium parameters

The illustrations in Fig. 1–3 indicate possibilities of the use of the proposed method for analysis of violations of equilibrium state of gaseous medium at the stage of early ignition of various materials. Important features of the proposed method of operative frequency-temporal representation are its relative simplicity, as well as the use of data of observation in real time. In this case, frequency-temporal representation is formed operatively upon arrival of the data of actual observation, i.e. in current time. The results of the method operation depend on two parameters: the width of the window for current frequency-temporal representation and the width of the smoothing window. The values for these parameters are selected based on the requirements for fast response and quality of frequency-temporal representation. For the presented results, the width of the window for the current frequency-temporal representation k=10 counts, and the width of the window for smoothing w=20 counts.

Frequency-temporal representations, shown in Fig. 1–3, indicate efficiency of the proposed method, as well as prove reliability of the stated assumptions about the features of dynamics of gaseous medium parameters at early ignitions in premises. The obtained results show that in the absence of ignitions, fluctuations of hazardous factors represent stationary and weakly correlated stochastic processes, characterized by small enough energy (less than 0.1 units) and a relatively wide frequency spectrum of fluctuations (over 0.5 Hz) for most of the studied materials. The above features of the studied fluctuations are explained by the chaotic nature of the motion of molecules and particles of gaseous medium. The emergence of ignitions causes a local violation of equilibrium state of gaseous medium and appearance of characteristic fluctuations of the studied parameters, translated by gaseous medium to registration sensors. The fluctuations contain information about the time and the rate of processes of violations of equilibrium state of gaseous medium. This information is reflected in an increase in the values of the represented functions of frequency-temporal representation (from 0.5 to 60 units. depending on the test material and the registered parameter of gaseous medium), as well as in a decrease in the width of the spectrum of fluctuations (less than 0.2 Hz). Thus, for example, in Fig. 1–3, the regions of violation of equilibrium state of gaseous medium correspond to discrete time values, approximately equal to the 200^{th} count – the ignition time of the simulation chamber of the correspondent test combustible material. In this case, following Fig. 1–3, fluctuations of the registered parameters of gaseous medium at the initial ignition stage are really of complex non-stationary nature. In this regard, it should be considered that it is a true assumption that in order to detect early ignitions by fluctuations, it is necessary to study their combined temporal and spectral characteristics.

9. Conclusions

1. The obtained frequency-temporal representations in the absence of ignitions qualitatively characterize an insignificant level (modular value does not exceed 0.1 unit) and a relatively wide (over 0.5 Hz) spectrum of fluctuations compared to the interval of ignition start, which proves their weak correlation. The occurrence of ignition leads to an increase of the modular value by one order and concentration of the spectrum in the narrow region of zero frequencies, characterized by less than 0.2 Hz. The nature of frequency-temporal representations for different combustibles qualitatively proves a complex nature of the studied parameters of gaseous medium.

2. Theoretical basis for development of the method of frequency-temporal parameters of gaseous medium is based on the ability of the medium to translate violation of its equilibrium state from the ignition source to the periphery in premises. In this case, the ignition source is considered a moving source of disturbances and parameters of the medium carry information about temporal and frequency shifts of disturbances. Following the obtained frequency-temporal representations, they are localized in time and frequency. In addition, localization time coincides with the beginning of ignition of material (in the vicinity of the 200th count), and frequency localization describes the rate of disturbance propagation in the medium. It was shown that these shifts of disturbances are characterized by the correspondent uncertainty function that is an invariant with respect to the double Fourier transformation, determined by a squared modulus of frequency-temporal energy density of the parameter.

3. The method of frequency-temporal representation of fluctuations of hazardous parameters of gaseous medium in real time of their observations was developed. The method is based on implementation of the equivalence of transformation of Fourier uncertainty function to the instantaneous spectrum or frequency-temporal energy density of the considered parameters of the state of gaseous medium. The merits of the proposed method include its relative simplicity compared with the known frequency-temporal representations and the use of data in real time.

4. Verification of the method was carried out based of experimental data of registration of basic gaseous medium parameters at an early ignition of alcohol, paper, wood, and textiles in the simulation chamber. Obtained operative frequency-temporal representations of fluctuations of gaseous medium parameters allow using it as a new method for detection of early ignitions at premises based of qualitative and quantitative differences of frequency-temporal representations for fluctuations of gaseous medium parameters at ignitions of different materials.

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