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RESULTS OF EXPERIMENTAL RESEARCH INTO CORRELATIONS BETWEEN HAZARDOUS FACTORS OF IGNITION OF MATERIALS IN PREMISES

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Представлені результати експериментального дослідження динаміки небезпечних факторів стану середовища в моделюючей камері, а також їх автокореляцій і парних кореляцій при різних лагах для спирту, паперу, деревини і текстилю. Встановлено, що інформативною ознакою раннього виявлення загорянь є ступінь взаємної кореляції флуктуацій факторів при нульовому лагу. Виявлено, що для розглянутих матеріалів ознакою раннього виявлення їх загоряння є коефіцієнт парної кореляції СО і температури при нульовому лагу, що має дуже високий ступінь кореляції

Ключові слова: раннє загоряння матеріалів, динаміка небезпечних факторів стану середовища, автокореляції факторів, парні кореляції факторів

Представлены результаты экспериментального исследования динамики опасных факторов состояния среды в моделирующей камере, а также их автокорреляций и парных корреляций при различных лагах для спирта, бумаги, древесины и текстиля. Установлено, что информативным признаком раннего обнаружения возгораний является степень взаимной корреляции флуктуаций факторов при нулевом лаге. Выявлено, что для рассмотренных материалов признаком раннего обнаружения их возгорания является коэффициент парной корреляции СО и температуры при нулевом лаге, обладающий высокой степенью корреляции

Ключевые слова: раннее возгорание материалов, динамика опасных факторов состояния среды, автокорреляции факторов, парные корреляций факторов

1. Introduction

Prevention of ignition in premises is one of the most important problems of safe development of community. This causes the relevance of development of systems of fire-prevention automatic equipment. Modern systems of fire-prevention automatic equipment must enable guaranteed early detection of ignitions in premises. Recently, there have been two main trends of development of systems of fire-prevention automatic. The first trend is connected with improvement of primary sources of information on hazardous factors of early ignition in the premises based on new data processing technologies and considers actual conditions [1–3]. The issues of creation of self-adjusted primary sources of information are explored [4, 5].

The other trend is based on group processing of information on hazardous factors of early ignition and networking technologies [6]. In the framework of this trend, the authors developed new technologies of joint processing of information on two or more factors for reliable early detection of ignition in the premises. First of all, it is development of technologies of multi-sensor ignition detection [7]. A part of these technologies has received the status of EN and ISO standards [8–10]. However, because of complexity and diversity of actual ignitions, while substantiating technologies of multi-sensor detection, the properties of major hazardous factors of ignition remain insufficiently studied.

In this regard, the study of the properties of major factors of ignition of combustible materials is relevant.

2. Literature review and problem statement

Nowadays, smoke sensors are commonly used as fire detectors [11]. They enable early detection of ignitions, have high performance and relatively low price. Other variants of fire detectors (FD) use gas detectors [12] or temperature sensors [13]. It is known that fire smoke sensors are characterized by high frequency of false alarm, caused by the temperature change [14]. That is why PD that combines several types of sensors enables more effective detection of ignitions and functioning of the entire fire alarm system [15]. Analysis of carbon monoxide (CO) as one of hazardous factors of early ignition has become even more important recently. That is why CO sensors are most often included in multi-sensor PD as one of the channels of obtaining information on hazardous factors of ignition. Each of the sensors of multi-sensor FD is sensitive to a certain type of ignition, and their totality makes it possible to distinctly identify a type of fire.

An important role for early detection of ignitions is played by pyrolysis processes. Currently, there are a lot of results of experimental and theoretical studies of pyrolysis of various materials. Research [16] is focused on studying of characteristics of combustion of plantation wood. Paper [17] studied the impact of velocities of heat release while burning larch under various conditions. In this case, two extremums of heat release velocity in the process of combustion were discovered. In article [18], efficiency of combustion was evaluated experimentally. In this case, linear relationship between average heat release velocity and combustion intensity is observed. Paper [19] studied heat release velocity of organic glass and cypress. Almost a linear relationship between heat transfer velocity of the material and radiation intensity was experimentally established. A similar result was also obtained for mahogany, southern pine, red oak and basswood. However, there are no data relating to autocorrelation and mutual correlation properties of hazards factors of ignition for typical materials of premises.

A special area for early detection of ignitions in the premises is the ceiling jet area, in which characteristic transformations of hazardous fire factors occur. Paper [20] presents results on temperature measurement for some modeling experiments in the ceiling jet area. In this case, the error was around 12 %. It is noted that such modeling error is permissible, since many fire parameters are evaluated with a high degree of uncertainty.

At present, the role of computational models for studying and prediction of dynamics of hazardous factors of ignition in premises is becoming increasingly important [21]. However, many models, such as models of combustion of materials, turbulence and heat transfer, use many different constants. For example, for atria, smoke amount depends, inter alia, on the volume of the air entering a combustion area, greatly depending on the turbulence model and dimensions of the ignition center. In addition, it is noted that these models need full verification by experimental fire tests [21]. In article [22], it is shown that mutual correlation of CO concentration and data of the ionization chamber during fire experiments in the premises allows us to reliably detect ignitions of test fire centers of EN 54 standard. Results of such experiments with consideration of interferences are presented in [23]. It was shown that by combining data on concentration of CO and smoke, it is possible to reliably detect most ignition centers in the face of interferences.

The above literature analysis suggests that joint dynamics and correlations of reported hazardous environmental factors at early ignition of materials in the premises have not been sufficiently studied so far. In addition, the results of these studies greatly influence the choice and development of technology of multi-sensor detection. First of all, it involves experimental studying of the properties of registered dangerous factors of environment. Therefore, an important and unresolved part of the problem of multi-sensor detection is experimental study of dynamics of states and correlations of recorded data on hazardous factors of early ignition in premises.

3. The aim and objectives of the study

The aim of present research is the experimental study of dynamics of the state, autocorrelations and pair correlations of hazardous factors of early ignition in premises for typical materials.

To accomplish the set goal, the following tasks had to be solved:

– to state the main tasks and conditions for the experimental study of correlations of hazardous factors of early ignition;

– to substantiate selection of theoretical base for carrying out the experiment;

– to study experimentally the dynamics of state, autocorrelations and pair correlations for hazardous factors of early ignition of typical combustible materials in the form of alcohol, paper, timber and textiles.

4. Main tasks and conditions for experimental study of correlations between hazardous factors of early ignition

Any premises are characterized by a specific fire load, which is determined by the amount of combustible materials and their properties. Dynamics of hazardous factors of ignition in premises depends not only on fire load, but also on the access of oxygen-enriched air, that is, on air exchange in the premises. A hotbed of early ignition is usually regarded as a source of a number of physical components in the form of ambient temperature, concentration of smoke and CO. That is why early detection of ignitions in premises can be performed based on the registration of specified components. In this regard, the main objectives of the experiment were:

– to explore dynamics of the state of the ignition center in the form of function of joint change of ambient temperature, smoke and CO concentration over time on the interval of absence of ignition (normal conditions) in premises, as well as on the interval of beginning of ignition of combustible material in the form of alcohol, paper, timber and textiles;

– to explore autocorrelation functions of ambient temperature, smoke and CO concentration on the interval of time of absence of ignition (initial condition) in premises and on the interval of the beginning of its ignition for relevant combustible materials;

– to explore mutual correlation functions of pair combinations of ambient temperature, smoke and CO concentration on the interval of time of absence of ignition (normal conditions) in premises, as well as on the interval of the beginning of ignition of appropriate combustible materials.

Experimental studies were conducted in a special test chamber [25], imitating non-pressurized premises at setting fire and combustion of tested combustible materials such as alcohol, paper, timber and textiles. The volume of the chamber was 0.524 m^3, in the upper part of the chamber there were sensitive sensors that registered physical components of ignition of appropriate combustible materials. In this case, the flame's height was less than 0.2 m. Data x_i about components of ignition of materials were registered using a heat detector TPT-4, an optical smoke detector DIP-3.2 and a carbon monoxide detector (Discovery).

Registered data from outlets of corresponding sensors were recorded in random access memory of the computer and the developed software allowed us to carry out scanning of relevant sensors at different time intervals. In this experiment, scanning of the sensors was performed at the time interval equal to 0.1 s. Fire was set to materials at discrete moment of time t_{200}, corresponding to 20 s. To explore correlations of the registered hazardous factors of early ignition, two similar by duration intervals of analysis, equal to 200 counts (20 s) were selected. In this case, the first interval was selected in the range of count 0 and count 200 and corresponded to the absence of ignition. The second interval was selected between counts 100 and 300 and covered the moment of starting of ignition of combustible material (setting fire), which corresponded to the middle of this interval.

Experimental study of the state of early ignition and correlation of its main factors was carried out for each of the indicated combustible materials in the following sequence: alcohol, paper, timber and textiles. Registration of dynamics of environmental factors in the chamber for each session of ignition of the indicated materials was carried within the time interval equal to 30 s. After each session of ignition, the chamber was naturally ventilated for 5–7 minutes to bring the factors of environment in the chamber to the state, which is close to the initial.

5. Theory behind the experiment

The environment in the chamber will be considered as a certain complex system, within which disturbance in the form of ignition of appropriate combustible material can exist. For such a system, it is possible to examine the state – the set of essential properties the system (environment in the chamber) possesses at a given moment of time, instant photo, "data sampling" of the system. The state is an internal feature of the system, the value of which at the present moment of time determines the current value of the source magnitude. In the present case, the current value of the source magnitude is determined by current values of ambient temperature, as well as concentration of smoke and CO in the environment. That is why, in order to solve the first problem of the experiment, we studied dynamics of the state of environment in the chamber on the intervals of absence of ignition (initial conditions) and beginning of ignition (disturbance) of materials, such as alcohol, paper, timber and textiles. Correlation of ambient temperature, concentration of smoke and CO on the intervals of absence of ignition and beginning of ignition was studied based on determining of respective autocorrelation and mutual (pair) correlation functions. Argument of correlation functions is the interval between two random values of respective registered state of environment. Autocorrelation and cross-correlation functions were determined based on the assumption that registered data about hazardous factors of the state of environment on limited intervals of analysis represent the samples from related random ergodic processes. Correlation functions were described by values of Pearson correlation coefficients for data of relevant factors, shifted in relation to each other by several counts over time. One of the operation formulas for calculation of correlation coefficient $r_{xy}(n)$ at the shift of the data for two arbitrary components X and Y of environment by n counts (lags) was determined as

$$r_{xy}(n)=\frac{\sum(x_j-\bar{x})(y_{j+n}-\bar{y}_n)}{\sqrt{\sum(x_j-\bar{x})^2\cdot\sum(y_{j+n}-\bar{y}_n)^2}}, \quad (1)$$

where $\bar{x}$ is the mean value of data of component X of environment on the interval of analysis; $\bar{y}_n$ is the mean value of data of component Y of the environment on the interval of analysis, shifted by n counts over time. It should be noted that correlation coefficient (1) is lagging and, compared to the others, possesses the best interpretability. However, it should be taken into account that it is best suited for evaluation of linear relationship between two arbitrary components with Gaussian distribution. In the case of non-Gaussian distribution of one or both components, it still characterizes degree of their linear relationship, but it was already impossible to apply methods for significance verification to it. To determine autocorrelation function for arbitrary component X, in expression (1), component Y was substituted for component X. In this case, statistical reliability of correlation coefficients (1) is preserved for the number of lags, which does not exceed a quarter of the total the number data counts on the analysis interval.

Due to absence of a strict theory about values of correlation coefficient, we will adhere to the following levels: very weak – from 0 to 0.2; weak – from 0.2 to 0.5; medium – from 0.5 to 0.7; high – from 0.7 to 0.9; very high – from 0.9 to 1.

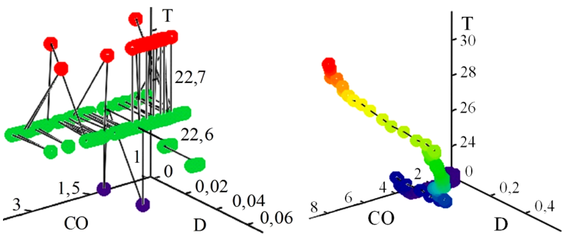
In accordance with the above theoretical information, the experimental studies, results of which are presented below, were performed.

6. Results of experimental study of correlations between hazardous factors of early ignition

Fig. 1 shows results of research in dynamics of registered factors (T –temperature, °C; CO – concentration of carbon monoxide, $x10^{-4}$ %; and D – smoke concentration, dB/m) of environment in the chambers for two intervals of analysis lasting for 20 s. In this case, the first interval (Fig. 1, *a*) corresponds to absence of ignition in the chamber, and the second one (Fig. 1, *b*) – to setting fire to alcohol in the middle of this interval.

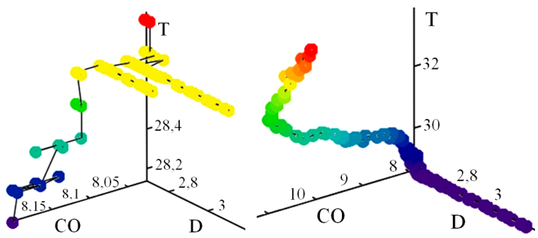
Similar results after natural ventilation of non-pressurized chamber for 5–7 minutes in the case of setting fire to paper, timber and textiles are shown, respectively, in Fig. 2–4.

Points in Fig. 1–4 correspond to discrete states of the studied hazardous factors of ignition on the intervals of data analysis. The color of points illustrates conditional level of ambient temperature in the chamber from the minimum level (purple) to the maximum level (red). Presented dependences include errors of factors' measurement by sensors, as well as errors of data registration when converting them into a digital form. In this case, digitization errors can be considered negligibly small compared with sensory errors. That is why the obtained data can be used for qualitative assessment of the nature of dynamics of the studied ignitions of materials taking into account sensors' errors. Given that in the experiment, sensors are the part of actual types of FD, assessment of correlations of hazardous factors, taking into account the errors of correspondent sensors, will be close to real.



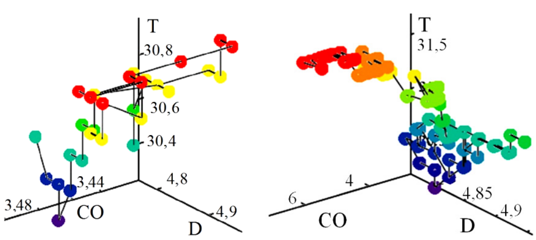
a *b*

Fig. 1. Dynamics of registered factors of environment state in the chamber for two intervals of analysis: *a* — absence of ignition; *b* — existence of ignition of alcohol in the middle of the interval



a *b*

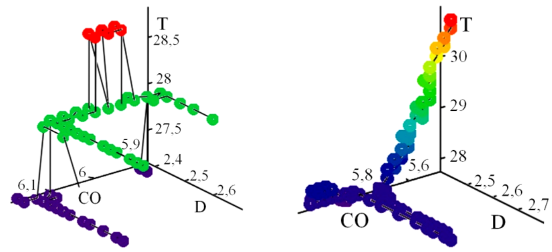
Fig. 2. Dynamics of registered factors of environment state in the chamber for two intervals of analysis: *a* — absence of ignition; *b* — existence of ignition of paper in the middle of the interval



a *b*

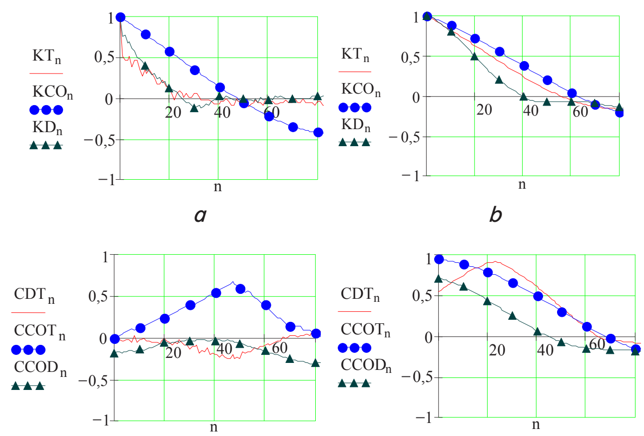
Fig. 3. Dynamics of registered factors of environmental state in the chamber for two intervals of analysis: *a* — absence of ignition; *b* — existence of ignition of timber in the middle of the interval

More detailed studies of environment factors in the chamber at ignition of different materials were based on determining of the respective autocorrelation and mutual correlation functions of the factors based on correlation coefficient (1) for various lags n. In this case, statistically reliable correlation for the considered intervals was determined for lags, not exceeding 50. Autocorrelation functions of temperature, smoke and CO in Fig. 5–8 are marked, respectively, CT_n, CS_n and CCO_n, and pair cross correlation functions – CST_n, $CCOT_n$ and $CCOS_n$.



a *b*

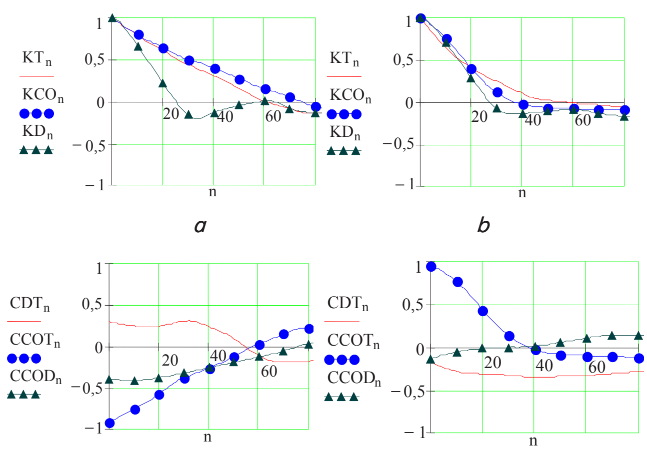
Fig. 4. Dynamics of registered factors of environmental condition in the chamber for two intervals of analysis: *a* — absence of ignition; *b* — existence of ignition of textiles in the middle of the interval



a *b*

c *d*

Fig. 5. Correlation functions of registered environmental factors in the chamber for two intervals of analysis: *a, c* — absence of ignition; *b, d* — presence of ignition of alcohol in the middle of the interval



a *b*

c *d*

Fig. 6. Correlation functions of registered environmental factors in the chamber for two intervals of analysis: *a, c* — absence of ignition; *b, d* — existence of ignition of paper in the middle of the interval

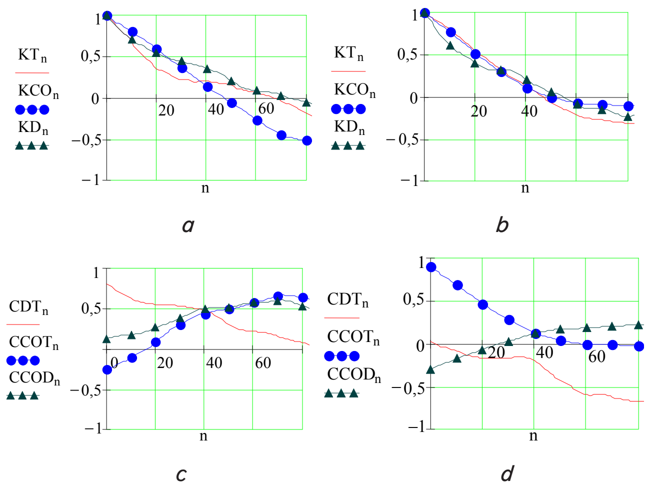


Fig. 7. Correlation functions of registered environmental factors in the chamber for two intervals of analysis: *a, c* – absence of ignition; *b, d* – existence of ignition of timber in the middle of the interval

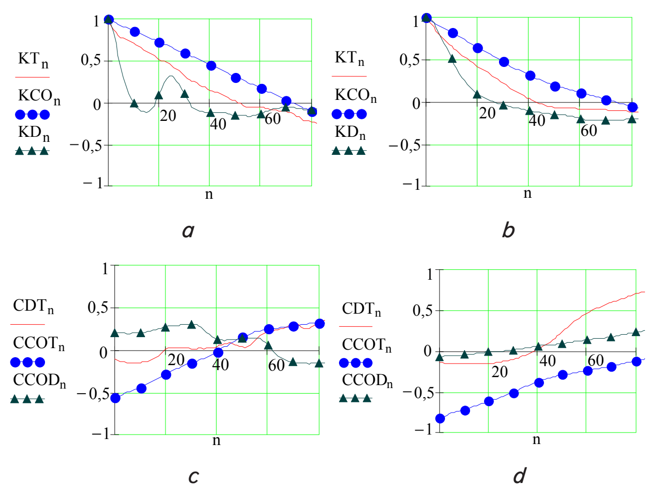


Fig. 8. Correlation functions of registered environmental factors in the chamber for two intervals of analysis: *a, c* – absence of ignition; *b, d* – existence of ignition of textiles in the middle of the interval

7. Discussion of results of research into correlations of factors of early ignition

An analysis of data in Fig. 1–4 shows that dynamics of factors of the state in the chamber before ignition of materials is locally inhomogeneous and distributed in space of factors with random transitions between local conditions. This is due to different influence of ignitions of preceding materials on the state of environment in the chamber, as well as impossibility of recreating identical conditions of natural ventilation of the chamber before ignition of the material that is next in the sequence. If there is an ignition, on the interval of analysis in the studied environment, one can see grouping of distributed local environmental conditions, observed prior to ignition. Random character of the grouped state of dynamics of environment continues, although it is different in nature for alcohol, paper and smoke and CO concentration.

Therefore, emergence of ignition of material leads to a corresponding transformation of the original dynamics of the factors of the state of environment. This means that indicated transformation can be used as an informative indicator of early detection of ignition in non-pressurized areas. In this case, it is possible to identify the type of combustible material in premises according to the nature of dynamics of the state of environment. Explanation of this fact can be the difference in complexity of the nature of physical transformations in gaseous medium when exposed to heat, smoke and carbon monoxide from the ignition center in the chamber. In this case, under normal conditions (before ignition) in gas medium of the chamber, there are occasional small fluctuations of the considered factors of environment regarding their stable states. On the whole, the general condition of environment, defined by the states of the considered factors, remains steady. In case of occurrence of any impacts in environment, its stability relatively to stable conditions is disrupted, resulting in a response change in dynamics of the relevant factors of environment. In this case, the indicated changes in dynamics of environmental factors in the chamber depend on the type of combustible material.

An analysis of data in Fig. 5–8 reveals that in the interval of analysis, corresponding to absence of ignition, dynamics of the studied environmental factors, characterizing the state, turns out to be quite similar. This is in line with the hypothesis of relative stability of the state of considered factors of gaseous medium, which was put forward. Divergences of stable dynamics that occur in this case were mentioned above. The degree of mutual pair correlations of the considered factors of gaseous medium in this case is assessed on average as weak or very weak. An exception is the case of the state of environment after the experiment with alcohol ignition. Degree of mutual correlation of CO and temperature at zero lag is assessed in this case as very high negative.

Analysis of autocorrelation functions indicated that the closest relationship between the values of each factor occurs at zero lag. This means that each of the factors is random and has no cycles and trends. In this case, with an increase in lag, degree of connection of values of the corresponding environmental factor decreases. Dynamics of factors' fluctuation is determined by their constant of time, which is numerically equal to the temporary lag, in which autocorrelation is close to zero. The results of the experiment suggest that presence of ignitions causes a slight increase in constant of time of fluctuations of the studied environmental factors. However, this feature of ignition appears not sensitive enough to be used as an indicator for early detection of ignitions in premises.

Analysis of the research results reveals that more informative indicator for early detection of ignition is a degree of mutual (pair) correlation of fluctuations of environmental factors (Fig. 5–8) at zero lag. This is explained by the random nature of development of changes of considered environmental factors at ignition of materials. In doing so, it was found that in the case of alcohol ignition, an additional indicator of ignition can be mutual correlation of smoke concentration and temperature (Fig. 5, *d*) for lag 20 (cyclical fluctuations with period of 2 s). According to the research results, it can be concluded that for all types of the studied combustible materials, an effective indicator for early detection of ignition is coefficient of pair correlation of temperature and CO at zero lag. At this, for alcohol, paper and timber, the indicated coefficient of pair correlation characterizes a very high degree of positive correlation, and for textiles – a very high degree of negative correlation.

A benefit of the present study lies in its novelty and obtaining of original, in our view, results, which are an attempt to identify experimentally the characteristics of early ignition of typical combustible materials in non-pressurized areas and their use in substantiation of methods and algorithms of functioning of multi-sensor FD. The shortcomings of the study can be considered the constraints, imposed by dimensions of the test chamber, location of sensors in the area of ascending jet and conditions of insufficient ventilation of the chamber after ignition of each material.

8. Conclusions

1. It was established experimentally that an informative indicator for early detection of ignitions is a degree of mutual (pair) correlation of fluctuations of environmental factors at zero lag. It was shown that for the considered types of combustible materials, an effective indicator of early detection of their ignition is coefficient of pair correlation of CO and temperature at zero lag. In this case, for alcohol, paper and timber, this coefficient of correlation is close to unity, and for textiles – to –1.

2. Coefficient of autocorrelation of factors and their pair correlations were determined based the Pearson lag correlation coefficient. Pearson lag correlation coefficient, compared to the others, possesses the best interpretability for applications. However, its use is limited to evaluation of a linear relationship of Gaussian factors. In the case of one or both factors are non-Gaussian, it still determines a degree of linear relationship of factors, but verification of significance makes no sense.

3. It was established experimentally that dynamics of factors of state of environment in the chamber before ignition of materials is locally inhomogeneous and distributed in space of factors with random transitions between local states. In case of existence of ignitions in the studied environment, there occurs grouping of distributed local state of environment, the character of which depends on material of ignition. It was established that the character of grouping can be used as an informative indicator for early detection of ignitions in non-pressurized premises, as well as for identification of the type of combustible material in premises.

4. Existence of ignitions causes a slight increase in constant of time of fluctuations of the studied environmental factors. However, this indicator of ignition appears not sensitive enough to be used as an indicator of early detection of ignitions. It was found that the more informative indicator of early detection of ignitions is a degree of mutual (pair) correlation of fluctuations of environmental factors at zero lag. In case of alcohol ignition, an additional indicator can be mutual correlation of smoke and temperature at lag 20. It was found that for combustible materials, such as alcohol, paper, timber and textiles, an effective indicator of early detection of ignition is coefficient of pair correlation of CO and temperature at zero lag. In this case, for alcohol, paper and timber, it is noted that pair correlation coefficient is close to 1, and for textiles – to –1.

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