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DEVELOPMENT OF A METHOD FOR RAPID IGNITION DETECTION BASED ON CURRENT SELECTIVE DISPERSION OF HAZARDOUS PARAMETERS OF THE GAS ENVIRONMENT

The object of the study is the current sample dispersion of arbitrary hazardous parameters of the gas environment during the ignition of materials. A theoretical justification of the method of operational detection of ignitions based on significant deviations of the current difference of sample dispersions of the measured arbitrary hazardous parameter of the gas environment has been carried out. In this case, the significance of the current difference of sample dispersions will allow detecting the ignition occurrence in real-time observation of an arbitrary hazardous parameter of the gas environment. The method allows setting the level of significance for the current deviation and ensuring the maximum power of fire detection. Laboratory experiments were conducted to verify the proposed method. At the same time, the differences of sample dispersions of hazardous parameters of the gas environment correspond to the general sets of reliable absence and occurrence of ignition. The results of the verification showed that at a given level of significance, the method allows detecting current ignitions of materials based on significant deviations of sample dispersions of the considered parameters of the gas environment. It was found that the most sensitive in terms of ignition detection are the CO concentration and the temperature of the gas medium. The maximum rate of increase in the CO concentration during the ignition of alcohol, paper, wood and textiles are 0.7 ppmm^2/s, 0.3 ppmm^2/s, 6.4 ppmm^2/s, 0.0025 ppmm^2/s, respectively. During the ignition of alcohol and paper, the rate of temperature increase is about 1°C/s, and during the ignition of wood and textiles – 0.25°C/s, respectively. The practical importance of the research lies in the use of significant deviations of the sample dispersions of parameters of the gas medium for the detection of material ignition.

Keywords: *ignition detection, sample dispersion, hazardous parameter, gas medium, material ignition.*

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1. Introduction

Safety is the main need of humanity. One of the reasons for the violation of human safety is fires. Fires cause death and injury to people, damage or completely destroy their property and various objects. According to world statistics [1], the largest number of fires (55%) occurs in residential buildings. The maximum material losses from fires are characteristic of industrial (45%) and residential (35%) objects. At the same time, the maximum number of deaths is due to fires in residential buildings (80%). It is known that any fire occurs due to ignition. If the ignition is eliminated in time, there will be no fire. At the same time, modern fire protection systems ensure the detection of the occurrence of a fire [2]. This means that at the time of the start of extinguishing the fire, the combustion process is already developed and uncontrolled. Extinguishing a fire at this stage becomes a difficult task, and in some cases practically impossible. It is possible to save a building in such conditions only by ensuring the normalized limit of fire resistance of structures [3]. In this regard, the prompt detection of ignitions (ID) in order to prevent fires is an urgent problem that requires a timely solution.

Fire detectors are used to detect fires, which monitor the concentration of CO, temperature, specific optical density of smoke [4] or other hazardous parameters (HP) of the gas environment (GE) [5]. The main disadvantage of traditional means and technologies is the impossibility of early fire detection (EFD), i. e. the impossibility of the ID of materials at an early stage of their development. This is explained by the fact that fire detection occurs when the GE HP values of the corresponding thresholds are exceeded. During the HP spread from the location of the ignition material to the detector, such a process can go from the ignition stage to the stage of full development. In [6], an intelligent fire alarm system is studied that uses ultraviolet radiation technology in the range of 185–260 nm and signal reception using a special aspherical lens. Achievements in the field of data processing technologies, identifiers and microelectronics, taking into account a deeper understanding of the physics of fire, are considered in [7]. It is noted that in practice, modern fire detection technologies have limitations in terms of error, increased response time, and are complex and expensive to implement. The technology of using dynamic structures of images of the area of possible fire occurrence for the purpose of their detection is studied in [8]. The paper considers the features of processing dynamic structures in real time. However, a model of only the dynamic structure of the fire image is proposed. Other fire NPs are not considered. Deep learning methods for increasing the efficiency of fire detection systems are studied in [9]. At the same time, the priority of strengthening the synergy between deep learning methods and remote sensing technologies for the development of more effective and accurate fire detection systems is noted. However, the obtained research results cannot be used for detecting fires in premises. In addition, [9] does not study the main fire NPs and their dynamic properties at the early stage of fire development. The work [10] is devoted to improving existing RVP systems.

It is proposed to use addressable fire detectors instead of conventional ones. However, such detectors have limitations regarding the detection time of exceeding the set thresholds by the measured parameters [10]. At the same time, the statistical GE HP properties regarding their sample dispersions are not used. In [11], new fire detection technologies based on the use of ultraviolet and Fourier spectral analysis are proposed. However, the use of Fourier analysis requires a guaranteed condition of stationarity for the processes of observation of the specified HPs. However, in conditions of ignitions, the GE HP dynamics is clearly non-stationary [12]. In [12], it is noted that the features of the current real dynamics of the GE HPs during the occurrence of ignitions are complex, non-uniform, individual and nonlinear. In this regard, it is proposed to use the current estimate of the GE HP bispectrum for the ID. However, the disadvantage of the current estimate of the bispectrum is the complexity of its formation in real time. This limits the possibilities of using bispectrum estimation for operational fire detection. Simpler methods of parametric and nonparametric statistics for identifying features of the dynamics of the NS GS for operational fire detection are not considered. In [13], it is proposed to use operational fire detection systems based on the use of various image sensors for fire detection. Such sensors allow remote measurement of the intensities of image pixels caused by the occurrence of material ignition. A common disadvantage of ID technologies based on image sensors is their low efficiency, associated with the significant time required for collection, processing and fire detection in real conditions. The use of image sensors for EFD in the presence of smoke and fire is investigated in [14].

The disadvantage of [14] is the use of complex algorithms for color image analysis and various machine learning methods. In this case, the EFD effectiveness based on image sensors in real conditions is significantly reduced. In [15], it is proposed to use the assessment of the bicoherence of the GE HP dynamics for EFD purpose. The magnitude of the bicoherence of the GE HP dynamics allows detecting nonlinear effects in the dynamics. However, the possibilities of assessing the ID quality based on bicoherence are not considered. In addition, the use of bicoherence for ID is associated with a complex procedure for processing data on the HP.

Thus, the main cause of fires is the ignition of materials. Solving the EFD problem is impossible without operational ID of materials. In this regard, the development of operational ID methods with a quantitative assessment of the quality of detection based on measurements of current GE HP carried out by traditional sensors should be considered an unresolved part of this problem.

The aim of research is to develop a method for rapid detection of ignitions in premises with a given reliability based on current sample dispersions of hazardous gas environment parameters monitored by fire detectors. This will allow for rapid signaling of ignitions of materials for their timely extinguishing to prevent advanced fires in premises with significant losses.

2. Materials and Methods

The object of research is the current sample GE HP variance during the ignition of materials. The current sample variance differs from the generally accepted sample variance in that it is determined by a sample that is tied to the current time. This means that the current sample variance is determined by a sample that is characterized by the current GE HP observation and observations that were made earlier. The hypothesis of the study was that the values of the current sample variance of the observed GE HP in the absence and presence of ignition of materials are different. Experimental studies were carried out in a special laboratory chamber [15]. Alcohol, paper, wood and textiles were selected as test materials (TM). The controlled GE HPs were the CO concentration, optical density of smoke and temperature [16]. GE HPs were controlled by appropriate sensors. The temperature was monitored by a digital thermometer DS18B20 (DallasSemiconductor, USA), smoke (specific optical density of HS) – SPD-3.10 (Arton, Ukraine), CO concentration – by the MQ-7 module (HengxinElectronicFactory, China) [17].

The processing of the obtained data at the rate of discrete GE HP control was performed using the Mathcad 14 software environment. The GE HP control sensors were fixed in the upper part of the laboratory chamber, where the characteristic inhomogeneities of the GE HP occurred when the TM ignition occurred. It was assumed that the features of the impact of the TM ignition on the controlled GE HPs in the laboratory chamber are identical to the features of the impact in real rooms [18, 19]. Forced ignition of the TM was carried out approximately in the interval between 220 and 260 discrete control of the GE HPs. This allowed to assume that the controlled GE HPs until the moment of the TM ignition (up to 220 counts) correspond to the reliable absence of the TM ignition in the chamber. The study used methods of mathematical statistics, namely the sampling method and the method of statistical hypothesis testing [20, 21]. Samples from GE HP observations were taken from two general populations. The first general population corresponded to the reliable absence of TM ignition. The second general population was current and corresponded to GE HP observations with an unknown moment of possible ignition of the material or its absence. From the GE HP observations corresponding to the specified populations, samples of a fixed size were selected, which included 100 discrete observations each. The relationship between the current time t of the observation and the number of the current discrete observation was determined by the function $[t/0.1]$. The specified sample size ensured the representativeness of the sample variances for the specified populations, as well as the approximation of the distributions of the sample variances to the Gaussian law [20].

3. Results and Discussion

An important component of complex object protection systems is EFD systems, which allow to significantly reduce the risk of human death and significant destruction of objects [22], as well as negative impact on the environment [23]. It is known that for a fixed-size sample h of observations $x_1, x_2, ..., x_k$, where $k = 1, 2, ..., h$ of an arbitrary GE HP, the complete characteristic is the sample distribution function $F(x)$ [24]. However, the use of the sample function $F(x)$ for operational safety is a difficult task. Therefore, often instead of the sample function $F(x)$ itself, its approximate characteristics are used in the form of various sample moments. The most widely used are sample moments that characterize the mathematical expectation and the dispersion of the sample relative to the mathematical expectation (sample variance or sample standard deviation). When materials burn, the observed GE HPs are characterized by an increase in the average values and dispersion. At the same time, a significant GE HP dispersion can significantly distort the sample means and lead to errors in the ID. Since the dispersions do not depend on the mean, the use of current sample GE HP dispersions for operational ID is the most promising compared to the use of current sample means [20, 21]. Taking this into account, let's assume that the controlled GE HPs can be caused by both the absence and the

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occurrence of material ignition. This means that part of the controlled GE HPs can belong to the general population, which corresponds to the absence of ignition, and part to the general population, which corresponds to the occurrence of ignition. In this case, operational ID is reduced to determining which of these general populations the current sample of controlled data belongs to.

To justify the method, let's assume that there are two general sets of current values of controlled GE HPs. Let the first general set of controlled data be due to the reliable absence of ignition. Let's consider this general set as the training set, and the sample of controlled data from this set as the current training sample. Let's assume that the second general set of controlled data can be due to both the absence and occurrence of ignition. Let's consider this general set as the verification set, and the sample of controlled data from this set as the current verification sample. Taking this into account, the task of operational ID can be formulated as the task of testing a simple hypothesis against a complex alternative. As a simple (null) hypothesis (H0), let's consider the hypothesis that the current sampling variance of the sample from the verification population of controlled GE HPs is equal to the training sampling variance of the sample taken from the training population, which corresponds to the reliable absence of fire. The complex hypothesis (H1) will be that the current sampling variance of the sample from the verification population of controlled HS NPs is greater than the training sampling variance of the sample taken from the training population, which corresponds to the reliable absence of ignition. Let's suppose that there is a current sample of controlled GE HPs of free size $h1$: $x(1)$, $x(2)$,..., $x(h)$, where $h = 1, 2,..., h1$, belonging to the training population. According to the proposed method, for each discrete time moment t, a current sample of size $g2$ of the GE HP control is formed: $x(t-1)$, $x(t-2)$,..., $x(t-g)$, where $g = 1, 2,..., g2$. In this case, the condition that $g2 \le h1$ is satisfied for the sample size is met. In general, the selection of sample sizes $h1$ and $g2$ should be carried out taking into account contradictory requirements – the accuracy of the ID moment and the error of representativeness of the current sample variances. It should be taken into account that with a decrease in the sample size, the accuracy of the ID moment increases, but the errors of representativeness increase. In addition, for small sample sizes, mathematical difficulties arise in assessing the ID reliability [24]. Therefore, let's use the condition of large sizes $h1$ and $g2$ with respect to the current samples. This will allow to assume that the distribution of the corresponding current sample variances approaches Gaussian [24]. According to [25], for the current sample variances of controlled GE HPs, a sufficient condition can be considered to be the sample size determined by 100 discrete values. At the same time, for the representativeness of the current sample variances of the samples for the corresponding general populations, it is sufficient to use samples which size exceeds 40 discrete values. In this regard, the final sample size for the proposed method can be chosen equal to 100 discrete values. At the same time, the conditions for the approximation of the distribution of the current sample variances to Gaussian and their representativeness will be ensured. This will allow to draw statistical conclusions based on them.

The current sample variances $D1$ and $D2_t$ for samples from the training and testing general populations will be determined in the form:

$$D1 = \sum_{i=1}^{m1} \left(x(i) - X1 \right)^2 / h1, \quad (1)$$

$$D2_t = \text{if}\left(t \ge h1, \sum_{i=1}^{n2} \left(x(t-i) - X2_t \right)^2 / g2.0 \right), \quad (2)$$

where $X1 = \sum_{i=1}^{m1} x(i)/h1$, $X2_t = \text{if}\left(t \ge h1, \sum_{i=1}^{n2} x(t-i)/g2.0 \right)$ – current values of sample means for the corresponding samples of controlled GE HPs; $m1$, $n2$ – number of controlled data in the samples.

The proposed method is based on testing the two considered hypotheses H0 and H1 for the current difference (1) and (2). In this case, the method of operational VT will be based on the study of the value of the current difference $D2_t - D1 = D_r$, which can be performed on the basis of the theory of standard errors [25]. Given that, the proposed method is reduced to testing the simple hypothesis H0, that the current difference $D_r = 0$, against the complex alternative H1, that $D1 < D2_t$. Testing the specified hypotheses is based on determining the corresponding critical region. The specified critical region will be determined by the current standard error $\sqrt{d1^2/h1 + d2_t^2/g2}$, increased by r times. In this case, the value r is characterized by the probability of the current normalized difference of variances falling into the region of acceptance of the hypothesis H0, which would be equal to the given ID probability (given significance level α). Since the normalized difference D_r when the hypothesis H0 is valid has an asymptotic symmetric distribution with respect to zero, the desired value r will be determined by a symmetric point with the opposite sign [20, 21]. Let's consider that the probability of the normalized current difference falling into the interval $(0, \infty)$ when the hypothesis H0 is valid is 0.5. Then the value r will be determined by the argument r of the probability integral function $\varphi(x) = \int_0^x e^{-z^2/2} dz / \sqrt{2\pi}$, which is equal to the value $(0.5 - \alpha)$. Taking this into account, finally the method of operational ID with a given reliability can be presented in the form of the following rule

$$D_r > r\left(d1^2/h1 + d2_t/g2 \right)^{0.5}. \quad (3)$$

The value of r in (3) is constant and is determined by the given ID probability (given significance level α). Method (3), which is based on testing the considered hypotheses at an arbitrary discrete time point $[t/0.1]$ for a given ID probability, will provide the maximum ID probability [20]. For the inverse rule, the probability of correct ID may be less than the given ID probability. In order to simplify the implementation of the proposed method, it is proposed to choose the same and equal sample sizes for the considered general populations $h1 = g2 = p$. Denoting by R the value $r(d1^2/h1 + d2_t/g2)^{0.5}$, method (3) can be represented as

$$D_r > R, \quad (4)$$

where R – the current ID threshold, which takes into account the given probability of false ID (significance level α) and the current error in calculating the current difference D_r.

Thus, the proposed method is based on determining the current sample variances for the training and testing populations, calculating the current difference of the specified sample variances and comparing the obtained difference with the current threshold. Experimental verification of the proposed method of operational ID (4) was carried out on samples from the current values of the controlled CO concentration, the amount of smoke (controlled specific optical density of GE) and the GE temperature in the laboratory chamber during the ignition of alcohol, paper, wood and textiles. Fig. 1–3 show the dependences of the dynamics of the difference D_r (red curves) and the threshold R (blue curves) for the significance level $\alpha = 0.05$ and the sample size $p = 100$ from the considered discrete controlled GE HPs during the ignition of the indicated TM. The abscissa axis indicates the numbers of the current discrete measurements. The designation $t/0.1$ on the abscissa axis means the integer part of the indicated ratio, which is a dimensionless quantity and determines the number of the discrete control. The interval of forced ignition of the TM is indicated by vertical dashed lines.

Before the ignition of paper, wood and textiles, the value of the current difference D_r of the CO concentration is close to zero (Fig. 1, *b*, *c*, *d*). When materials are ignited, the current difference D_r for the CO concentration significantly exceeds the current threshold and has a positive sign. At the same time, in Fig. 1, the results confirm that the ignition of materials is characterized by a different nature of the non-uniformity of the current difference D_r for the CO concentration. Thus, according to the data in Fig. 1, *a*, it was established that during the ignition of alcohol, the non-uniformity is close to a jump-like character (the growth rate is approximately 0.7 ppmm^2/s). At the same time, in Fig. 1, the dynamics of the difference of the sample dispersions at the moment of ignition turned out to be less than zero. This is explained by the fact that the current sample dispersions are random variables that can take on different possible values. Therefore, their difference can have a different sign. In this case, the given difference between $D2_t$ and $D1$ turned out to be negative. Following the method (4), a decision is made about the absence of ignition in the interval from 0 to 220 counts. In this case, this decision is characterized by the maximum probability of the correct decision for a given probability of an incorrect decision [19, 20]. The time of occurrence of a jump-like change in the current difference D_r for observing the CO concentration practically coincides with the ignition of alcohol. When paper ignites, there is also a close to jump-like increase in the current difference D_r relative to the controlled CO concentrations, but it is characterized by 0.3 ppmm^2/s. At the same time, there is a shift in time of the IM moment by approximately 4 s. For wood, similar indicators of the increase in the current difference D_r and the shift in ID time when observing the CO concentration are approximately 6.4 ppmm^2/s and 3 s, respectively.

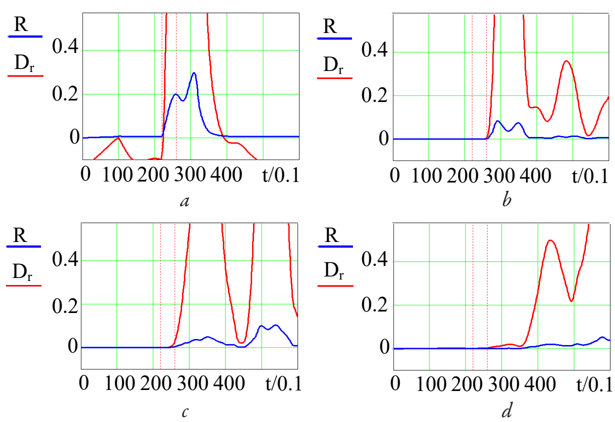

Fig. 1. Dynamics of the current difference of sample dispersions and the current threshold for the CO concentration during the ignition of: *a* – alcohol; *b* – paper; *c* – wood; *d* – textiles

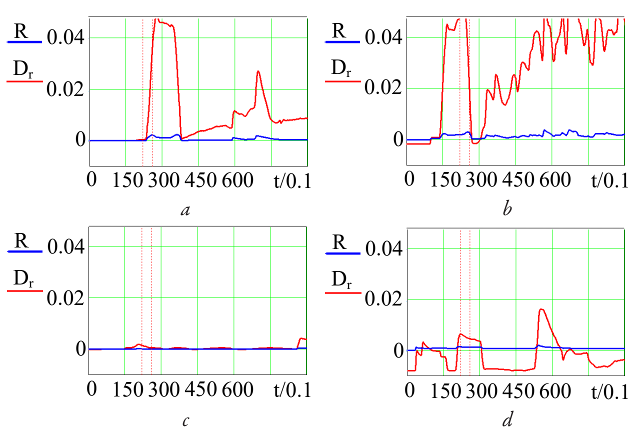

Fig. 2. Dynamics of the current difference of sample dispersions and the current threshold for the specific optical density of GE during ignition: *a* – alcohol; *b* – paper; *c* – wood; *d* – textiles

In the case of textile ignition, similar indicators of a slight increase in the current difference D_r when observing the CO concentration are approximately 0.0025 ppm/s and 0 s, respectively. At the same time, 7 s after the material is ignited, the current difference increases, which is characterized by approximately 0.04 ppm/s. These results do not contradict the known results and are explained by the different specific burnout rates of TM [26]. The dynamics of the current difference D_r when controlling the specific optical density of GE for smoke (Fig. 2) indicates that when alcohol ignites, the indicator of the increase in the current difference D_r for the controlled specific optical density of GE in the case of smoke control is approximately 0.02%. At the same time, this effect is observed almost at the moment of ignition of the material (Fig. 2, *a*). When other materials are ignited, the indicator of the increase in the current difference D_r for the controlled specific optical density of GE has a similar value at the moment of ignition. However, when wood and textiles are set on fire (Fig. 2, *c*, *d*), the growth rate of the current difference D_r for this GE HP is an order of magnitude smaller compared to the ignition of alcohol and paper (Fig. 2, *a*, *b*). For the current difference D_r when controlling the GE temperature when igniting alcohol and paper, the growth rate is approximately 1°C^2/s almost at the moment of ignition (Fig. 3, *a*, *b*). When wood and textiles are set on fire, the growth rate of D_r when observing the GE temperature is approximately the same and is about 0.25°C^2/s (Fig. 3, *c*, *d*). The time of appearance of the growth of the current difference D_r for the above materials for the moment of their ignition is approximately 3 s. The obtained results experimentally confirm the overall efficiency of the proposed method (with a delay from 0 to 3 s) of the ID of the studied TMs, taking into account the hidden and complex mechanism of the influence of the combustion products of materials on the controlled GE HP chambers. It was found that the most appropriate from the point of view of operational control with a given reliability are the current differences D_r of controlled CO concentrations and GE temperatures. The exception is materials with a low specific burnout rate (wood and textiles). Less appropriate from the point of view of operational control is the current difference D_r in the case of GE specific optical density. But this is not a drawback of the developed method, but is explained by the individual characteristics of ignition and combustion of TM. A limitation of the study is the need to place GE HP control sensors in the ceiling zone of the chamber [26], where significant fluctuations of controlled GE HPs occur. At the same time, the disadvantage is that the verification of the method was limited to a finite set of TMs and controlled GE HPs in the laboratory chamber. Further development of the study should be aimed at overcoming the noted limitation and disadvantage.

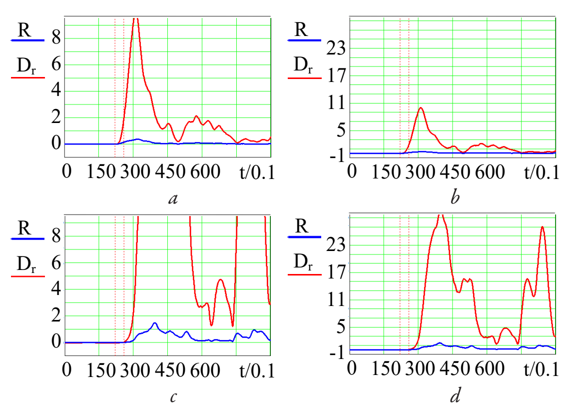

Fig. 3. Dynamics of the current difference of sample variances and the current threshold for the GE temperature during ignition of: *a* – alcohol; *b* – paper; *c* – wood; *d* – textiles

4. Conclusions

A theoretical justification of the method of rapid ignition detection with an assessment of the reliability of detection based on the use of current sample variances of controlled hazardous parameters of the gas

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environment of premises has been carried out. The method is based on testing a simple hypothesis that the current sample variance of controlled hazardous parameters of the gas environment is equal to the sample variance of controlled hazardous parameters of the gas environment of the same parameter in the reliable absence of ignition. At the same time, the alternative hypothesis is complex and consists in the fact that the current sample variance of controlled hazardous parameters of the gas environment is greater than the sample variance of controlled hazardous parameters of the gas environment in the absence of ignition. An experimental verification of the proposed method has been carried out. It has been established that rapid ignition detection is based on significant differences between the current sample variance of controlled hazardous parameters of the gas environment and the sample variance of observations in the absence of ignition. The results obtained generally confirm the ability of the proposed method to promptly detect the ignition of test materials, taking into account the hidden complex mechanism of interaction of ignition materials with hazardous parameters of the gas environment in the laboratory chamber. It has been established that the most appropriate from the point of view of prompt detection of ignition is to control the temperature and CO concentration of the gas environment.

Conflict of interest

The authors declare that they have no conflicts of interest in relation to this research, including financial, personal, authorship, or other, that could affect the paper and its results presented in this article.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of the presented work.

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