Advances in Science and Technology
ISSN: 1662-0356, Vol. 170, pp 133-141
doi:10.4028/p-4Wts69

Submitted: 2025-04-28
Accepted: 2025-06-16
Online: 2025-11-10

Study of the Accuracy of the Temperature Fire Measurement by the Sensors of the Fire Alarms in Dynamic Conditions with Random Temperature Fluctuations

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Keywords: sensor of the ambient temperature measurement, fire alarm, accuracy of measurement, temperature, dynamic conditions, random fluctuations.

Abstract. The results study of the accuracy of the temperature fire measurement by the sensors of the fire alarms in dynamic conditions with random temperature fluctuations, are presented. The statistical study of the accuracy measurement is based on the method of transformation of the random processes by the linear systems. The constructive approaches to optimizing and the accuracy improvement of the thermal sensors with the thermo-resistant sensitive element and the bridge measuring circuit in the dynamic conditions under random temperature fluctuations based on the choice of corresponding values of the characteristic parameter of the sensor and the constant time of its sensitive element have been proposed. Scientific novelty of the results is in the development model and in the method of analysis of the dynamic model of the thermal sensors with the thermo-resistant sensitive element in the form of a thin plate. It has been proved that the invariance of the accuracy of the ambient temperature measurement over time is possible. The obtained results allow solving the practical tasks determining the optimal parameters of the sensors under the conditions of fire temperature dynamics, taking into account the background random temperature fluctuations.

1 Introduction

At present, the sensors for temperature measurement are widely used in the various fields of human activity. One of the important areas of their application is fire protection facilities. In different systems of the fire automation the sensors of the temperature measurement are the main and sometimes the only source of primary information about the fire at the objects [1]. For example, in the fire alarm systems on the basis of this information the warning signal about the fire is formed [2] and the control signals for automatic fire extinguishing are generated. In this regard, the thermal sensors of the automatic fire systems demand the increased requirements for the precision of the ambient temperature measurement. In the real fire conditions the dynamics of the ambient temperature is unsteady and unpredictable by nature and is accompanied by the random background fluctuations [3]. Particularly high requirements for the precision of the temperature measurement are placed to the sensors used in the systems of early fire detection [системи раннього виявлення] when the initial dynamics of the ambient temperature from the fire source is masked by the background thermal fluctuations [4].

The sensors of the temperature measurement are particularly essential for the protection of the zones where there are occasional rapid changes in temperature or there are significant changes [5]. For example, it may be warehouses, commercial kitchens, technical rooms and energy facilities [6, 7]. There are methods for improving the accuracy of the temperature measurement sensors for automatic fire systems in dynamic conditions based on the reduction of inertia [8–10]. It should be noted that this approach is valid only in the absence of the random dynamics and background ambient temperature fluctuations during the fire. If these conditions are not met, the reduction of the sensors inertia during the real fire will result in the increased fluctuation error of determining the ambient temperature measurement (the reduction of the sensors accuracy) and, accordingly, in the increasing number of errors and false fire detections [11].

A large number of the research papers have been devoted to the accuracy of the sensors of the ambient temperature measurement. A considerable part of them refers to the temperature measurement sensors used in the systems of the fire-prevention automation. This is explained by the particular importance of solving the problem of providing reliable fire protection for modern objects [12]. In this regard, in recent years the intensive research in the sphere of improving the accuracy of the sensors of the automatic fire systems that are designed to measure the temperature of the ambience in terms of random fluctuations in temperature has been carried out [13–16]. A large number of the studies are devoted to the improvement of the sensors' accuracy based on their grouping and further processing of the initial information of each sensor group [11, 14, 15]. For example, the multicriterion technology of the processing of the sensor groups offers the most promising methods for improving the accuracy of temperature measurement and detection of actual fires at the objects [16, 17]. These technologies allow processing the output information of the sensors, which measure the various parameters of the ambient temperature dynamics (i.e., its absolute value, the rate of growth, or its fluctuations) [18]. However, the issue of studying the accuracy and optimization of the sensors themselves has not been considered in these works.

Some researchers are devoted to the use of the methods of fuzzy logic and neural networks to detect the conditions associated with the presence or absence of early fire [19, 20]. The method of the multi-criterion fire detection by a group of sensors, which are located in different areas of the object, is considered in [21]. It is proven that the grouping of sensors in the processing of information, taking into account the topology of their location, current time, and implemented measurement technology, enables high-quality fire detection at the object. There are also new fire detection technologies based on DS-theory methods [14] and coordinated optimization of dual detection [15]. The technology of the special placement of the sensors, which takes into account the peculiarities of the objects of protection, is considered in [22, 23]. It is noted that, based on the obtained data, it is possible to determine the required parameters for fire protection systems of the objects and their devices. Despite the findings of these studies, the issues of the accuracy and optimization of each sensor in the group have not been considered. This means that the problem of the accuracy improvement of the ambient temperature measurement, and on this basis, the guaranteed detection of fires at the objects [24] is solved only by the group principle and/or the placement of the group sensors without the possibility of accuracy improvement of the sensors themselves. Under this approach, the issues associated with the optimization and improvement of the sensor’s accuracy in the same group is artificially excluded.

The optimization of sensors in real conditions, taking into account the random temperature fluctuations not considered. It should be noted that the potential possibilities for reliable early fire detection in such conditions can only be achieved by using optimal accuracy sensors in conjunction with the principle of group processing of the output information and the optimal placement at the object of protection. A much smaller part of the known results is devoted to the optimizations of sensors and improvement of the accuracy of ambient temperature measurement based on the optimal synthesis of thermal sensors [16]. In this research, it is shown that the existing sensors of the ambient temperature measurement, which are used in the fire alarms of the automatic fire detector systems, are suboptimal for accuracy. Low accuracy and not optimization of such sensors are the main reasons for the increasing number of false fire detections and misfires at the real objects. In the paper [16] synthesis of the thermal sensor is designed for the general case without consideration of the sensitive element type and its parameters.

Due to the wide spreading of the fire automation of the thermo sensors with the thermo resistant sensitive element and the bridge measuring circuit in the fire alarm systems, it becomes quite difficult to take advantage of the general results [17] to optimize the accuracy of measuring the ambient temperature of inflammation in the real conditions. Therefore, the research in the field of optimization and to improve the accuracy of temperature measurement sensors based on the thermo-resistant sensitive element and the bridge measuring circuit is particularly relevant at the stage of modernization of the fire-prevention automatics.

2 Main Part

The most widely used thermal sensors of fire alarms are parametric measuring circuits. Such circuits convert the impedance of sensitive elements into a corresponding electrical signal in the form of voltage or current. Resistive elements are often used as sensitive elements, and for example, the Wheatstone bridge circuit is used as a measuring bridge circuit [25]. One of the bridge diagonals is connected to a constant voltage source, and a load in the form of, for example, an amplifier is connected to the other. Usually, the internal resistance of the source is significantly less than the resistance of the load. In this case, the sensitivity of the measuring bridge is a maximum in the case of its equilibrium. The thermal processes in the sensitive element are described by the equation of the unsteady heat conduction with the appropriate initial and boundary conditions [26]. Important for early detection of fires are the dynamic conditions of the thermal sensor application, characterized by the linear law of the environment temperature increase TC(t)=TH+bt, where TH is the initial value of the gas environment temperature, and b is determines the rate of its increase during the ignition of materials on background the randomise fluctuation of temperature. The values of TH and b characterize the individual features of the ignition of a specific material on the object. We will assume that for a single Fourier criterion (Fo=1), the environment temperature TC(t), caused by the ignition source, is accompanied by the additive effect of random temperature fluctuations N(t). The process N(t) is characterized by a zero mean value and a correlation function $k(\tau) = \sigma^2 R_N(\tau)$, where σ^2 the process power and the function $R_N(\tau)$ describe the correlation features of random temperature fluctuations. Usually, the inertial properties of the thermal sensor significantly exceed the correlation time τ_k of temperature fluctuations N(t). Therefore, instead of the process N(t), we can consider an equivalent process in the form of white noise with an intensity $G = 4\sigma^2\tau_k$.

2.1 Research methods

Let the initial voltage u(0) at the output of the thermal sensor be a random variable with the mathematical expectation m0 and the variance D0. In this case, the required output voltage of the thermal sensor should correspond to uT(t)=TH+bt–To, where To is the initial temperature of the material of the sensor's sensitive element. For this case, the dynamics of the mathematical expectation of the output signal will be described by an equation of the form:

$$B\frac{dm_u}{dt} + m_u = \xi(T_C - T_0),\ m_u(0) = m_0. \qquad (1)$$

In (1), the coefficients B and ξ are determined by the corresponding parameters of the dynamic model of the first approximation for the generalized thermostat of the thermal sensor. The general solution of equation (1) is determined as:

$$m_u(t) = m_0 e^{-\frac{t}{B}} + \xi\{(T_H - T_0)(1 - e^{-\frac{t}{B}}) + b\,B[e^{-\frac{t}{B}} + (\frac{t}{B} - 1)]\}. \qquad (2)$$

Based on (2), for the steady state we obtain

$$m_u(t) = \xi[(T_H - T_0) + b\,(t - B)]. \qquad (3)$$

Using the well-known general equation for determining correlation moments, in the case under consideration we obtain the following equation for the dispersion Du of the output voltage

$$B\frac{dD_u}{dt} + 2D_u = \xi^2\frac{G}{B},\ D_u(0) = D_0. \tag{4}$$

By integrating (4), we obtain an equation for the dynamics of the output voltage dispersion in the form:

$$D_u(t) = D_0 e^{-\frac{2t}{B}} + \xi^2\frac{G}{2B}. \tag{5}$$

In the case under consideration, the variance of the required voltage and the mutual correlation of the output and required output voltage are equal to zero. In this regard, the variance of the thermal sensor error will be equal to the variance of the output voltage (5). Taking into account the representation (5), the mathematical expectation of the temperature measurement error $m_\varepsilon(t)$ at the required output voltage uT(t)=TH+bt–To will be determined by

$$m_\varepsilon(t) = [m_0 - \xi(T_H - T_0 - b\,B)]e^{-\frac{t}{B}} + (\xi - 1)(T_H - T_0) - \xi b\,B + bt(\xi - 1). \tag{6}$$

Taking this into account, the variance of the error of the thermal sensor, determined by the second initial moment of the output voltage and characterizing the accuracy of measuring the temperature of the environment during the ignition of materials under conditions of random temperature fluctuations, will be determined by the expression:

$$\alpha 2y_\varepsilon(t) = m_\varepsilon(t)^2 + D_0 e^{-\frac{2t}{B}} + \xi^2\frac{G}{2B}. \tag{7}$$

The value of α2yε(t) in the general case, following (6) and (7), depends on the time and characteristic parameters of the thermal sensor and random temperature fluctuations in the environment during ignition of a specific type of material in the object. In the particular case when the characteristic parameter ξ of the sensor is equal to one, the second initial moment α2yε(t) of the error in measuring the temperature of the environment by the thermal sensor in the stationary mode, characterizing the accuracy of the measurement, does not depend on time and will be determined by the value:

$$\alpha 2y_\varepsilon = (b\,B)^2 + \frac{G}{2B}. \tag{8}$$

From expression (8) it follows that for thermal sensors there is an optimal parameter B for a specific character of random temperature fluctuations in the environment, at which the value of α2yε is minimal. The optimal values of the parameter B of the thermal sensor, following (8), will be determined by the value:

$$B_{opt} = \left[\frac{G}{4b^2}\right]^{1/3} \tag{9}$$

From expression (9) it follows that the optimal parameter Bopt of a thermal sensor for specific random temperature fluctuations in the environment, described by the correlation function $k(\tau) = \sigma^2 R_N(\tau)$, will be determined by the value

$$B_{opt} = \left[\frac{\sigma^2\tau_k}{b^2}\right]^{1/3}. \tag{10}$$

This means that the optimal parameter B_{opt} of the thermal sensor nonlinearly depends on the rate of temperature increase of the environment when the material on the object ignites, as well as the power and correlation interval of random temperature fluctuations in the environment.

2.2 The results of the study

Fig. 1 illustrates the dependence of the dynamics of the value $\alpha 2y_{\varepsilon}(t,\xi)$ for the three values (10, 1, 0,1) of the characteristic parameter ξ of the sensor and the dynamics of the temperature change, which is determined by the place of inflammation, is determined by the dependence 29+0,1*t* and is observed due to the background of the temperature fluctuations with the intensity *G*=1. In this case, the initial temperature of the sensitive element of the sensor is *T*o=25 degrees, and the value *B*=60 s (according to EN54).

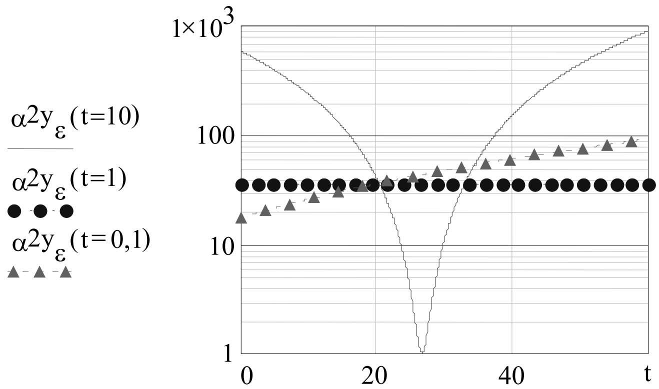

Fig. 1. Dynamics of the value $\alpha 2_{\varepsilon}(t,\xi)$ for the characteristic parameter ξ, which is equal to 10, 1 and 0.1, respectively

Fig. 2, 3 show the dependence of the lg(α2yε)=ES3ε on the characteristic parameter ξ and the time constant B sensor for the fixed time t=10 c under similar conditions, but at different values of the velocity b of the increase of the ambient temperature from the inflammation, equal to 0.5 and 0.017 degrees per second respectively (according to EN54).

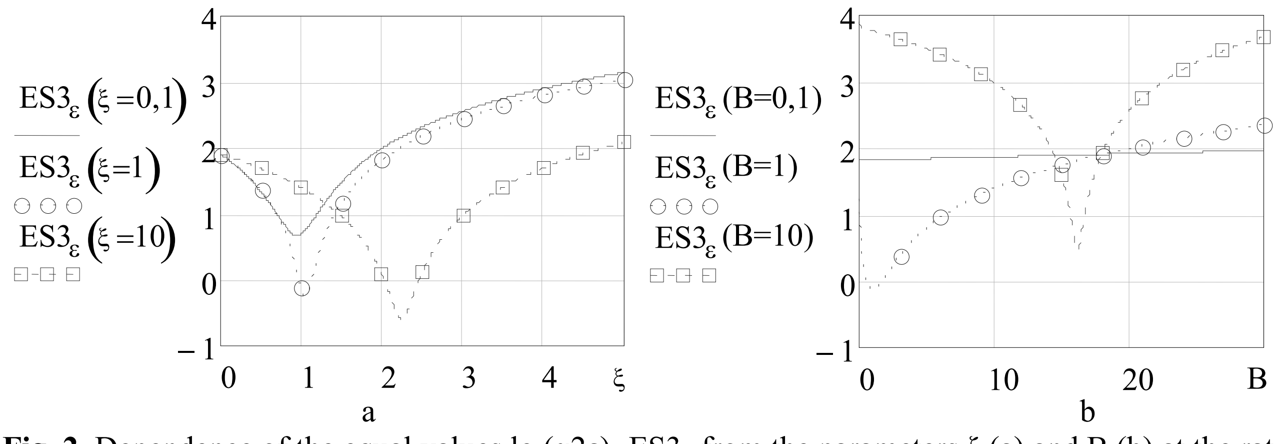

Fig. 2. Dependence of the equal values lg (α2ε)=ES3ε from the parameters ξ (a) and B (b) at the rate of the temperature increase of 0.5 deg/s

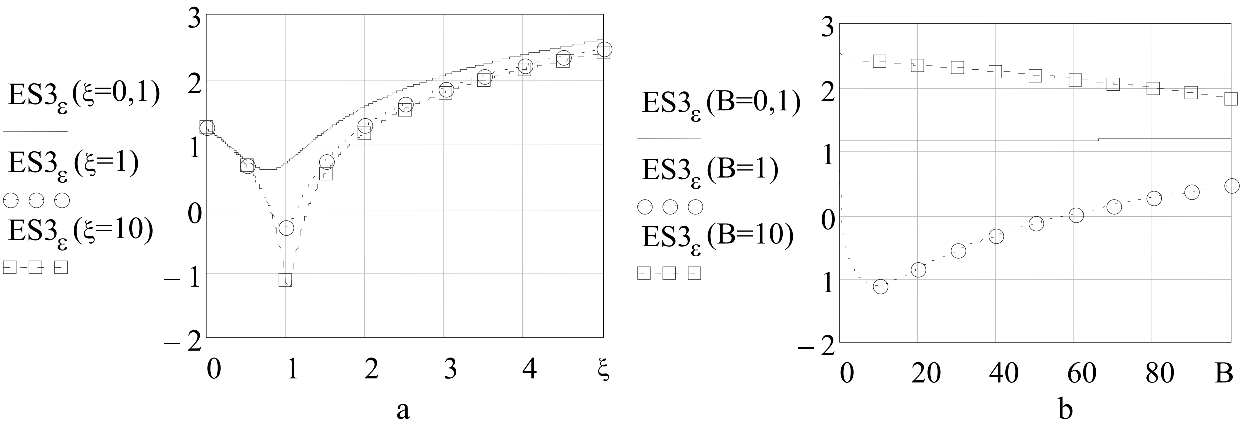

Fig. 3. Dependence of the equal values of the measurement error of lg(α2ε)=ES3ε from the parameters ξ (a) and B (b) at the rate of the temperature increase of 0.017 deg/s

Figures 4 and 5 illustrate the dependence of the equal values of the optimum constant time of the sensor B_{opt} determined by the ratios (9) and (10) for the temperature measurement, which are characterized by the different rates of the temperature rise and intensity of the random temperature fluctuations. For example, the data in Fig. 4 correspond to the conditions of high dynamics of the ambient temperature. In Fig. 5, similar data correspond to the conditions of low dynamics of the ambient temperature caused by the fire.

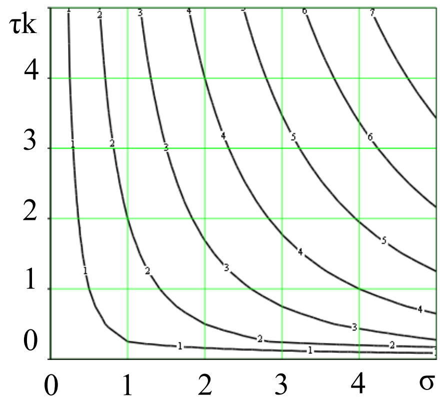

Fig. 4. Dependence of the optimal constant time B_{opt} on the random temperature fluctuations (σ, τ_k) in the environment at the rate of the temperature increase of 0.5 deg/s

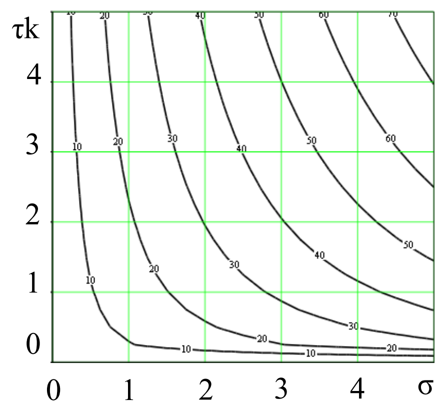

Fig. 5. Dependence of the optimal constant time B_{opt} on the random temperature fluctuations (σ, τ_k) in the environment at the rate of the temperature increase of 0.017 deg/s

The data obtained (Fig. 1) indicates that the maximum accuracy of the sensor in the conditions under consideration for the given values of the characteristic parameter ξ corresponds to the beginning of the fire outbreak. Fig. 1 also shows that if the characteristic parameter ξ sensor is equal to one, the accuracy is invariant over time. Therefore, to ensure the accuracy of the temperature measurement with the thermal sensor, it is expedient to choose the appropriate parameters for which the parameter $\xi=1$ is characteristic. It is established that in the case of $\xi<1$, there is a decrease in accuracy as the time of temperature measurement increases. If $\xi>1$, then at the initial moment the measurement accuracy is significantly low, as the time of temperature measurement increases, there is a tendency for the accuracy to increase to a certain time moment of the measurement, after which there is a further accuracy decrease in the measurement which increases with measurement time. This means that when selecting the sensor parameters for which $\xi>1$, the accuracy of the temperature measurement is maximum, but only for a certain moment in the measurement time.

The logarithm dependence of the error lg(α2ε) on the characteristic parameter ξ and the constant time B of the sensitive element, shown in Fig. 2, 3, for a fixed moment t=10 c under conditions of intensity G=1 randum fluctuations and for the velocities of temperature rise of 0.5 and 0.017 degrees per second, indicate the presence of some areas of high accuracy of measurement. At the same time, these areas depend on the rate of temperature increase due to the fire. Therefore, there are possibilities to optimize the accuracy of measurement by choosing the characteristic parameter of ξ sensor.

From the analysis of the data in Fig. 4 and Fig. 5 it follows that the characteristic parameters B (time constant) of the thermo sensors of the fire alarms, which equal 20 s and 60 s, according to EN54, are not optimal for detecting fires with the test speed of the temperature growth of the environment (according to EN54). Following the data obtained, given the accuracy of the ambient temperature measurement, the existing regulatory requirements for the characteristic parameter B are close to optimal only for the intense increase of the ambient temperature and no random fluctuations. This, perhaps, explains the low accuracy of detecting the actual fire outbreaks and the high probability of false determination of thermal fire alarms. As a result, the low efficiency of the existing systems of automatic fire signalling. Probably, the normative values of the constant time of the heat detectors specified in EN54 were chosen only if the maximum smoothing of the random fluctuations in temperature was taken without considering the presence of the first component in the expression (8). The dependencies presented in Fig. 4 and Fig. 5 allow for determining in practice the optimal values of B_{opt} for the thermal sensors of the fire alarms, depending on the conditions of their application at the objects (rate of the temperature environment increase from the fire, the intensity random temperature fluctuations, and the interval of correlation random temperature fluctuations).

3 Conclusions

In the paper, the study of the accuracy of the thermal sensors of the fire alarms with the thermo-resistant sensitive element and the bridge measuring circuit under the environmental increase from the fire and random temperature fluctuations. It is shown that under such conditions, it is possible to optimize sensors and increase the accuracy of temperature measurement based on a selection of generalized parameters of the sensor's sensitive element. To study the influence parameters of the sensitive element sensor on the realized accuracy of temperature measurement under conditions of an increase in the fire and random temperature fluctuations. Determination that, based on the time constant of the sensitive element, to optimize sensors and to increase the accuracy of temperature measurement. The scientific novelty of the results is in a theoretical analysis of the generalized scheme of the thermal sensors of the fire alarms with the thermo-resistant sensitive element in the form of a thin plate. The dynamic models allow for analyzing the accuracy and defining the approaches to the optimization and of accuracy improvement of the thermal sensor of the fire alarms with the thermo-resistant sensitive element and the bridge measuring circuit under realistic conditions. It has been established that in the general case, the minimum values of error depend on the characteristic parameter of the sensor, the constant time of the sensitive element, the current time, and the dynamics of the ambient temperature caused by the fire. It has been stated that there are possibilities to ensure the invariance in time of the ambient temperature measurement accuracy by the thermal sensor. The practical significance of the work lies in the obtained results that allow to solve the specific practical tasks in determining the optimal parameters of the thermal sensors of the fire alarms with the thermo resistant sensitive element and the bridge measuring circuit under realistic conditions of the fire detect at the object under protection taking into account the presence different of the random temperature fluctuations.

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