The object of this study was the change in temperature during a fire on transformers located in protective structures. Investigating the change in temperature during a fire on transformers located in protective structures is one of the priority tasks for protecting the economy and national security of the country. The studies solved the problem of fire resistance of the enclosing structures of protective structures in which the transformer is located. The fire resistance of enclosing structures has been confirmed by meeting the conditions related, in particular, to the calculated value of the critical temperature of the material.

The selection of the calculation scenario for investigating the temperature regime during a fire on a transformer located in a protective structure was carried out according to two scenarios of the occurrence and spread of fires. The study demonstrated temperature changes in the protective structure during the burning of the transformer based on data of the temperature sensor installed at heights of 1 m, 10 m, and 18 m above the place of occurrence of combustion. Certain conditions were taken into account for the calculation scenarios of the spread of fire and changes in the temperature effect on building structures. Cases when an automatic water fire extinguishing system is functioning and not functioning in the protective structure were taken into account.

In order to substantiate the temperature regime during a transformer fire, the conditions of the greatest impact of temperature on building structures were adopted. The following conditions were accepted: there is no automatic fire extinguishing system in the protective room; temperature sensor readings were located at a level of 18 m from the floor level of the protective structure. The calculation of the temperature regime during a transformer fire, which is located in the protective structure, was carried out using a field model, employing the reaction of simple stoichiometry (transformer oil can contain only carbon, hydrogen, oxygen, and nitrogen atoms).

Based on the results of this study, a modified temperature regime during a fire on transformers located in protective structures was substantiated. The maximum temperature range for a developed fire was from 900 °C to 1100 °C.

A standardized time (up to 30 minutes) has also been established during which the building structures of protective structures must withstand the effects of the modified temperature regime

Keywords: fire resistance limit, fire resistance class, temperature regime, transformer, critical infrastructure objects

UDC 614.841.41

DOI: 10.15587/1729-4061.2024.317332

SUBSTANTIATING THE PARAMETRIC TEMPERATURE MODE DURING A FIRE ON TRANSFORMERS PLACED INSIDE PROTECTIVE STRUCTURES

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Received 25.09.2024
Received in revised form 25.11.2024
Accepted 06.12.2024
Published 27.12.2024

***How to Cite:** Palchykov, R., Ballo, Y., Nizhnyk, V., Mykhailov, V., Gavryliuk, A., Loik, V., Synelnikov, O., Synelnikov, S., Stepanenko, V., Nuianzin, O. (2024). Substantiating the parametric temperature mode during a fire on transformers placed inside protective structures. Eastern-European Journal of Enterprise Technologies, 6 (10 (132)), 37–45. https://doi.org/10.15587/1729-4061.2024.317332*

1. Introduction

Transformers, as static electromagnetic devices, are an important link between distribution networks and power transmission lines. Transformers, as fire-hazardous types of equipment, contain from 200 l to 60,000 l of mineral oil, which is a combustible substance with a density in the range of (0.80–0.89)·10^3 kg/m^3. Under the conditions of Russian aggression, transformer equipment became one of the priority targets of remote bombing. Transformer fires are accompanied by overheating of the lubricant to a temperature of more than 250 °C, which is used as a coolant, destruction of the transformer housing, emergency spillage of lubricant from the transformer, and its burning.

To protect the transformer equipment, which is important for the economy and national security, from malfunctioning, their placement is possible in protected structures. Under such conditions, the leakage of boiling transformer oil and its ignition contributes to the further development of the fire and leads to its spread to the entire surface of the protective structure in which the transformer equipment is installed. Due to the wide variety of used materials and construction solutions, modern reinforced concrete structures have different resistance to fire. Therefore, methods for assessing the behavior of reinforced concrete structures under the influence of fire are extremely important. The above makes it necessary to establish requirements for the fire resistance of the enclosing building structures of such a protective structure. A scientific study on the substantiation of the parametric temperature regime during a fire of transformers of various classes located in protective structures is important and necessary in practice.

2. Literature review and problem statement

The behavior of reinforced concrete building structures exposed to the action of high temperatures is evaluated by experimental and calculation methods. The main criterion for the safe behavior of structures is the duration of thermal exposure, during which one of the limit states of building structures is reached. Works [1, 2] show that the experimental method is based on conducting fire tests of reinforced concrete structures in testing laboratories. This method is implemented with a standardized set of requirements (DSTU B V.1.1-4-98* Fire protection. Building structures. Fire resistance test methods. General requirements) for test installations, control and measuring equipment, samples of structures, the sequence of execution of test procedures and final processing of their results [3], etc. In [4], the issues of reproducing different types of temperature regimes and substantiating the scaling of test stands are investigated. However, the work does not include the study of temperature regimes of fire development in transformers. The studies show that a number of factors affect the reliability of tests when using the experimental method. Such factors are limitations on overall dimensions of construction samples in test facilities; the support system of the power units of the installations does not implement the current loads and the conditions for fixing the samples; when applying the results to real structures, the possibility of error, etc., is not taken into account. Thus, when evaluating the behavior of reinforced concrete structures under the influence of high temperatures, it is advisable to use the calculation [5, 6], which provides flexibility when taking into account the boundary conditions for reinforced concrete elements of building structures. Fire tests are ineffective, in particular, for evaluating the fire resistance of building structures connected in nodes. Such an assessment involves testing several structural elements, so a calculation method described by the logarithmic law [7, 8] can be applied, which is less expensive and time-consuming than fire tests.

It is believed that the basis of practical calculations for fire temperature prediction is often an integrated model using approximation formulas and nomograms. Such a model is the simplest calculation of the temperature regime of a fire in an enclosure; it assumes that the heat of the fire is used to heat the combustion products and is evenly distributed throughout the volume of the room. However, these calculations require the knowledge of the fire temperature in a first approximation to determine the air density, volumetric heat capacity, and the reduced degree of blackness of the combustion products under the given conditions. According to the authors of paper [9], when calculating up to 10 minutes, the fire does not have a standard temperature regime, and the formula for the initial temperature assessment does not work. Therefore, for a simplified determination of the fire temperature in the first approximation, the authors provide a method of calculation, in which the growth of the fire temperature can be accepted according to linear or logarithmic laws. The construction of buildings and structures of various purposes with the use of new enclosing structures leads to the need to solve non-stationary heat conduction problems.

The increase in the number of fires and the material damage caused by them, the lack of a sufficient testing base in Ukraine, and the expensive part of experimental research determine the importance of the tasks of improving the methods for calculating the fire resistance of reinforced concrete structures. Therefore, the existing method of calculating the strength of reinforced concrete sections taking into account the real laws of deformation and the results of the study of the effect of intense high-temperature heating on the nature of the complete "σ-ε" diagrams of concrete and reinforcement need significant correction. As a result of the research, work [10] provides a refined methodology for calculating the temperature distribution in cross-sections of reinforced concrete structures during multi-sided heating and cooling, taking into account the dependence of heat transfer characteristics on temperature. The given procedure makes it possible to increase the accuracy of fire resistance calculations of compressed reinforced concrete structures, to devise rational structural solutions with a guaranteed fire resistance limit.

Traditionally, a structural project is considered satisfactory if the regulatory fire protection requirements [11] are met, in particular regarding the preservation of the load-bearing capacity by the structural elements during the operation of the established nominal heating mode. In this case, an approach is used to characterize the fire load – the Eurocode parametric fire curve, which determines the burning temperature over a certain period of time. At the same time, the latest studies show that traditional methods do not provide adequate load-bearing capacity of reinforced concrete structures in the case of complete burnout of the combustible load. Therefore, there is a need to adopt a holistic approach in the design of buildings and structures. In this case, in [12], the concept of uncertainty of the model is investigated on the basis of ensuring the reliability of the designed fire-fighting measures. The stochastic correction factor for fire load density proposed in the work should be taken into account in protected and unprotected structures.

As is known, fires in buildings and structures are characterized by a heating phase, followed by a cooling phase. The destruction of reinforced concrete structures can occur during or after the fire extinguishing phase. However, the influence of the cooling phase on reinforced concrete structures has not been sufficiently investigated in modern approaches to the creation of structural projects. Accurate and effective assessment of the post-fire characteristics of tunnel structures is crucial to ensure their reliability. In [13], it was established that the main factors affecting the characteristics of shield tunnel structures after a fire are the depth of chipping, the depth of concrete failure, the reduction of concrete strength, the reduction of bolt strength, the area of chipping, the area of concrete failure, and the number of bolt failures. The authors propose a framework of five degrees of fire damage according to the relative load-bearing capacity of the tunnels after the fire.

A reliable and reliable method for determining the fire resistance limit of a structure is a method that, among other things, is based on the temperature distribution in the cross-section of the structure during full-scale fire tests. An alternative to this method is a less expensive and time-consuming general theoretical method based on the use of the structural component of the differential non-stationary heat conduction equation. Given the lack of a single universal technique, the main task in [14] was to devise a procedure for determining the temperature distribution in the cross-section of a reinforced concrete slab according to the standard fire temperature regime. The author of the work substantiated the further possibility of using these thermal indicators to evaluate the fire resistance of reinforced concrete slabs with any cross-section according to the simplified method recommended by Eurocode 2 (Design of reinforced concrete structures. Part 1–2. General provisions. Calculation of structures for fire resistance DSTU-NB EN 1992 -1-2:2012 (EN 1992-1-2:2004, IDT).

The above research results show that the substantiation of the temperature regime during a fire is an important aspect of ensuring the fire safety of people and the operational reliability of equipment. The study of the parametric temperature regime under fire conditions is associated with an interdisciplinary direction when scientists, engineers, representatives of industry and regulatory bodies cooperate. This enables a wide range of research and development in this important area. We also agree with the authors of works [15] that national standards, harmonized with Eurocodes, make it possible to calculate the fire resistance of reinforced concrete structures and, thus, to meet fire safety requirements at the design stage.

But the questions related to the substantiation of the parametric temperature regime during the fire on transformers of classes AT 750 kV and AT 330 kV, which became the priority targets of remote bombing during the period of Russian aggression, remain unresolved. In this regard, it is suggested to place transformers inside protective structures. Similar studies by domestic scientists regarding the substantiation of the parametric temperature regime during a fire had not been carried out before. All this gives reason to assert the expediency of conducting research on transformers of various classes located in protective structures, which is important and necessary in practice.

3. The aim and objectives of the study

The purpose of our work is to justify the parametric temperature regime during a fire on transformers of different classes placed inside protective structures. This will make it possible to introduce modern approaches to limit the spread of fire on transformer equipment, especially under conditions of Russian aggression, which is one of the priorities of protecting the economy and national security of the country.

To achieve the goal, the following tasks must be solved:

– to determine the initial conditions of the calculation scenario of a fire in building protective structures;

– to calculate the temperature regime during a fire on a transformer placed inside a protective structure;

– to justify the modified temperature regime during a fire on a transformer placed inside a protective structure.

4. The study materials and methods

The object of our study is the temperature change during a fire on transformers located inside protective structures.

The hypothesis of the research assumes that in the event of an emergency oil spill from the transformer in the volume of the protective structure, the temperature regime of a possible fire will not have a standard character of development. Identifying patterns of influence of the amount of transformer lubricant and geometric parameters of the protective structure will affect the process of evaluating the fire resistance of the enclosing structures of protective structures.

The scientific research was conducted using the following methods. A comprehensive analysis and generalization of previously performed works on the study of fire temperature regimes was performed. Mathematical modeling was carried out using the FDS software package of temperature change processes during a fire on transformers located inside protective structures using field methods. Finite difference methods according to the "predictor-corrector" scheme and finite volumes were used for solving differential equations. The Euler method was used to solve the system of Navier-Stokes equations during modeling of temperature change processes under fire conditions on transformers located inside protective structures; method of the presence of outliers and quasi-outliers in research results (Grubbs). The method for checking whether the variances of research results belong to one general population (Fisher) was also used; the dichotomy method for justifying the size of the computational grid of computer models; methods of mathematical statistics for processing research results.

Analysis of the properties of the load-bearing structure in terms of fire protection should be carried out taking into account the dependences set by the calculation situations for models of thermal and mechanical effects, as well as at elevated temperatures. Such requirements are stipulated by DSTU-NB EN 1990:2008 Eurocode. Fundamentals of structural design (EN 1990:2002, IDT). As a rule, fire resistance must be confirmed by the following criteria: time, strength, and temperature. Comparison according to temperature criteria is the most common method by which the ability to maintain the strength of the structure at critical temperatures and the ultimate load is determined, which is described using simplified calculation methods. As a rule, in most cases, nominal fire temperature regimes are used for the design of building structures: standard temperature regime; temperature regime of external fire; hydrocarbon temperature regime. Their time dependence is described by DSTU-NB EN 1991-1-2:2010 Eurocode 1. Actions on structures. Part 1–2. General actions. Actions on structures during a fire. Amendment No. 1 (EN 1991-1-2:2002, IDT+EN 1991-1-2:2002/AC:2013, IDT+NA:2013).

The hydrocarbon temperature regime refers to stricter regimes than the standard temperature regime. This temperature regime must be used when determining the class and limit of fire resistance of building structures used at energy industry facilities. The test temperature of such structures has higher regime values than when testing any other types of structures used in the public construction sector, as well as for their facing materials. Examples of dependences of such hydrocarbon temperature regimes of fire development (temperature versus time) are represented in the form of curves (Fig. 1) according to [16].

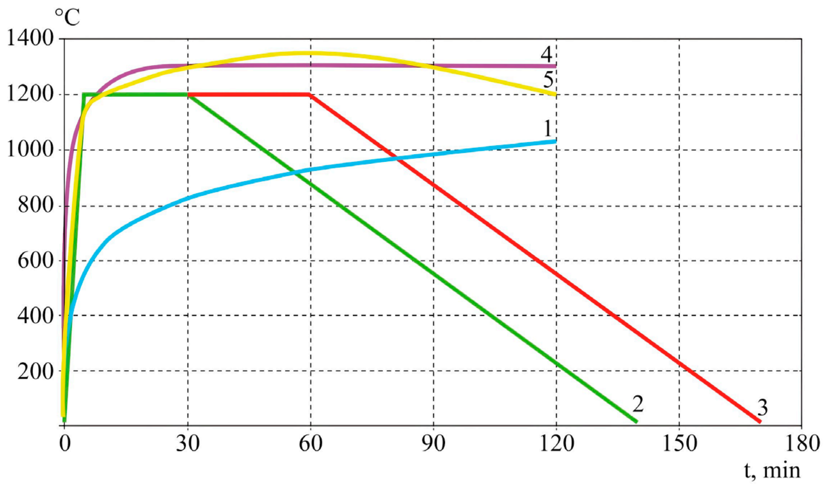


Fig. 1. Temperature modes of fire evolution: 1 – standard temperature mode of fire; 2 – RABT ZTV temperature regime for automobile tunnels; 3 – RABT ZTV temperature regime for railroad tunnels; 4 – temperature regime of a hydrocarbon fire; 5 – RWS temperature mode (simulates the burning of a fuel truck (50 m^3) in the tunnel) [16]

5. Results of investigating the parametric temperature regime during a fire on transformers

5. 1. Initial conditions for the calculated fire scenario of transformers placed inside protective structures

Taking into account current military threats, special requirements regarding fire resistance are put forward to the building structures of the transformer protection premises. The enclosing structures of these structures must, among other things, ensure a special temperature and humidity regime in the room during operation and protect the structure from surface and ground water. Climatic conditions of such structures provide for the parallel-serial operation of the system with two fans, each with a capacity of 35,825 m^3/h. The plan-scheme of the protective structure for placing the transformer is shown in Fig. 2.

When determining the conditions of the fire calculation scenario, the following should be taken into account: spatial and planning decisions; thermophysical characteristics of building materials of structures and placed equipment; type, quantity, and placement of other combustible substances and materials; type of automatic fire extinguishing and smoke protection system. The choice of the calculation scenario is based on the considerations in which the worst consequences for the further development of the fire are expected. At the same time, the following should also be taken into account: the initial source of the fire; possible dynamics of fire evolution; the algorithm of triggering and activation of the fire protection system. In this case, it is assumed that the fire occurs in the room with the largest fire load and the smallest volume.

Based on the above, two calculation scenarios of the occurrence and spread of fire were considered, namely:

Scenario 1 – a fire broke out in the room where the AT 330 kV class transformer equipment is located, the transformer oil spills onto the floor and spreads freely over the entire area of the room. The automatic water fire extinguishing system is not activated. The estimated area of the fire is 348 m^2, the height of the room is 18 m. The linear spread of the fire is assumed with a circular front. The initial parameters of the characteristics of the transformer lubricant for the calculation of the development of the fire are accepted taking into account the data declared by the manufacturer.

Scenario 2 – the fire broke out in the equipment room of the AT 750 kV class transformer; the transformer oil spills onto the floor and spreads freely over the entire area of the room. An automatic water fire extinguishing system is present and operated properly for 180 seconds. after the start of combustion. The estimated area of the fire is 348 m^2, the estimated height of the room is 18 m. The linear spread of the fire is assumed with a circular front. The initial parameters of the characteristics of the transformer lubricant are similar to those for the first scenario.

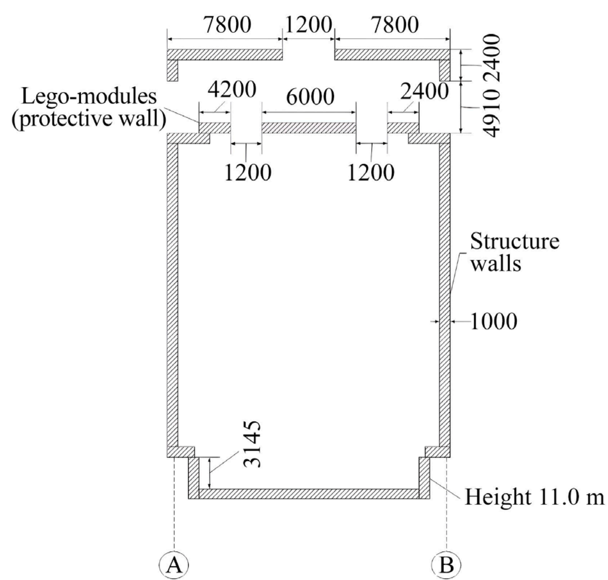


Fig. 2. Schematic diagram of the protective structure for a transformer

5. 2. Calculation of the temperature regime during a fire on a transformer placed inside a protective structure

Calculation of the temperature regime during the fire of the transformer, which is located inside a protective structure, was carried out according to the field model using the reaction of simple stoichiometry (transformer lubricant can contain only carbon, hydrogen, oxygen, and nitrogen atoms).

A special SmokeView software was used to display and visualize the simulation results of the FDS program. FDS implements a Computational Gas Dynamic (CFD) model of heat and mass transfer during combustion, which numerically solves the Navier-Stokes equation for low-velocity temperature-dependent flows, with particular attention to smoke propagation and heat transfer during fire. In its usual form, the system of Navier-Stokes equations [17–19] consists of two equations: the equation of motion and the equation of continuity.

The visualized 3D model of the protective structure with a transformer is shown in Fig. 3.

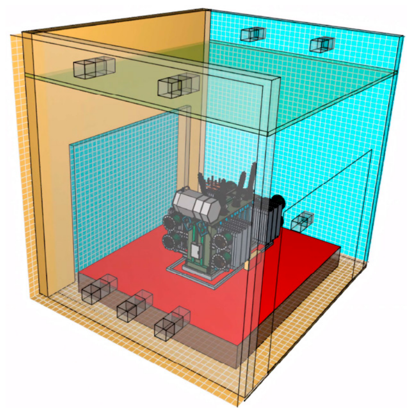


Fig. 3. A visualized 3D model of a protective structure with a transformer

According to the chosen fire scenarios, the burning takes place inside the room of the protective structure over its entire area during the entire simulation time (2000 s). Temperature sensors are placed directly around the perimeter of the room where the transformer equipment is located.

Fig. 4 shows the dynamics of temperature changes in the protective structure during the burning of the transformer according to the data of the temperature sensor installed at heights of 1 m, 10 m, and 18 m above the site of the fire, when the protective structure does not have an automatic water fire extinguishing system.

The sensor located at a height of 18 m from the floor level of the protective structure (Fig. 4, *a*–*c*) showed the highest temperature values. For further investigation of the temperature regime of the fire, it is enough to have readings from the temperature sensors, which are placed at a height of 18 m from the floor level of the protective structure.

Fig. 5 shows the dynamics of temperature change in the protective structure during the burning of the autotransformer according to the data from the temperature sensors installed at a height of 18 m above the site of the burning. For this case, there is no automatic water fire extinguishing system in the protective structure.

The results of checking for the presence of emissions and quasi-emissions according to the Grubbs criterion [20] are shown in Fig. 6.

Thus, the results indicate that the obtained temperature data at the initial stage mark individual emissions and quasi-emissions, so such data of the results should not be taken into account during their further processing.

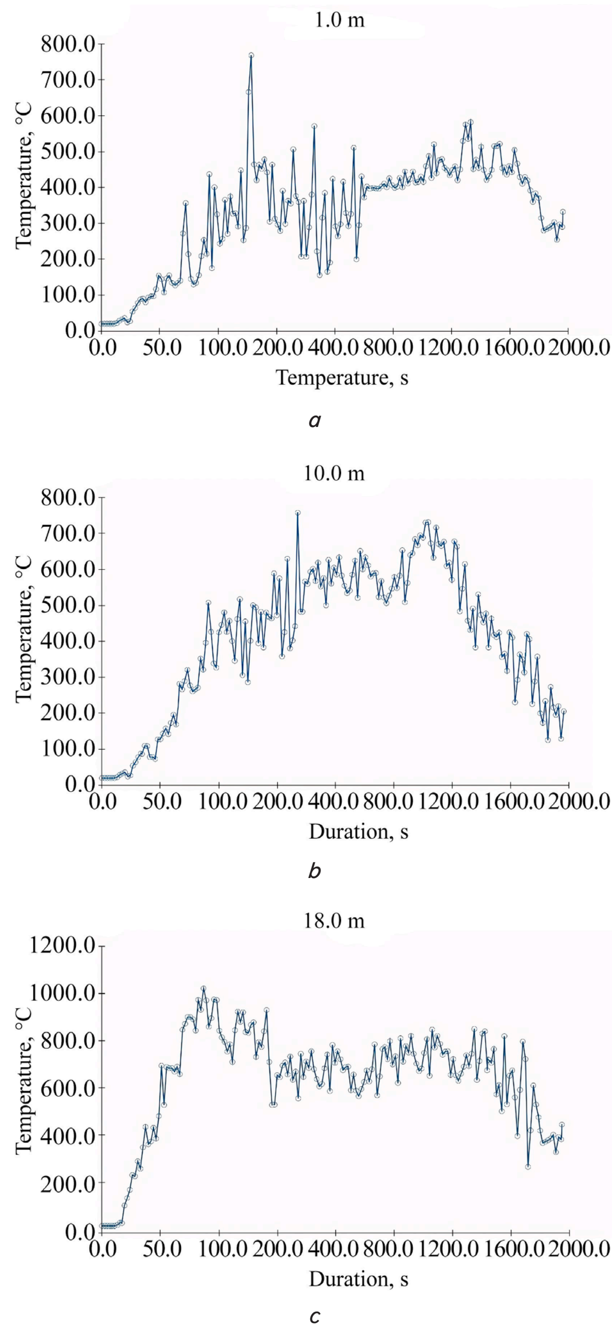


Fig. 4. Dynamics of temperature changes in the protective structure during the burning of the transformer according to the data from a temperature sensor installed at heights of 1 m, 10 m, 18 m above the place of fire, when the protective structure does not have an automatic water fire extinguishing system:
a — for the installation level of temperature sensors of 1 m;
b — for the installation level of temperature sensors of 10 m;
c — for the installation level of temperature sensors of 18 m

Fig. 7 shows temperature changes in the protective structure during the burning of the autotransformer according to the data from the temperature sensor installed at heights of 1 m, 10 m, and 18 m above the site of the burning. In this case, the protective structure has an automatic water fire extinguishing system.

According to these plots, a similar situation is observed with regard to the highest temperature values on the sensor, which is located at a mark of 18 m from the floor level of the protective structure. Fig. 8 shows the dynamics of temperature change in the protective structure during the burning of the autotransformer according to the data from the temperature sensors installed at a height of 18 m above the site of the burning. In this case, the protective structure has an automatic water fire extinguishing system.

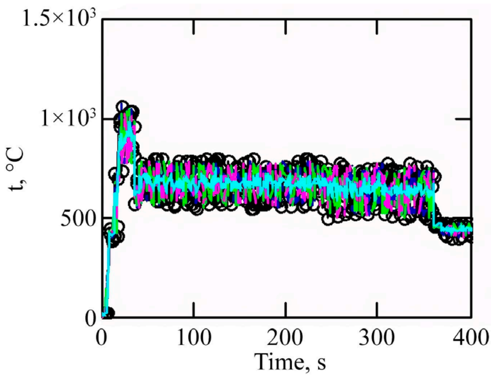


Fig. 5. Temperature changes in the protective structure during the burning of the autotransformer according to the data from temperature sensors installed at a height of 18 m above the site of combustion, when the protective structure does not have an automatic water fire extinguishing system

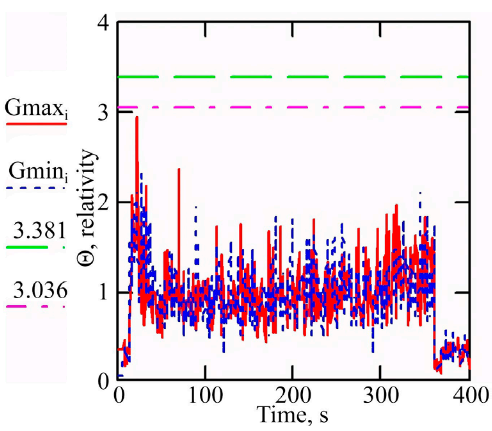
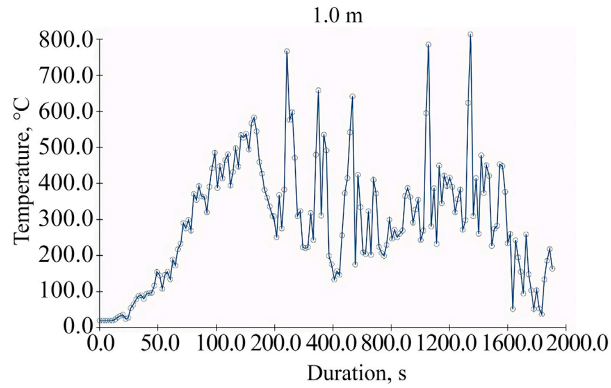


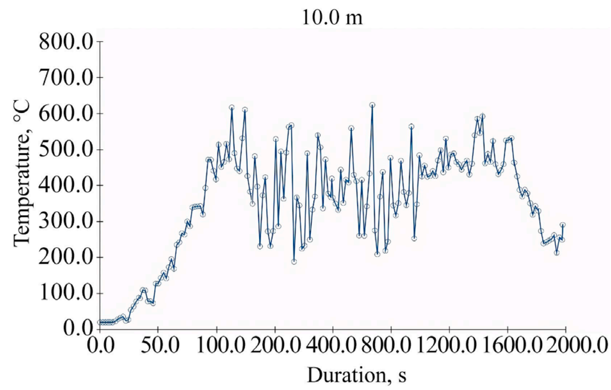
Fig. 6. Results of checking the studies for the presence of emissions and quasi-emissions according to the Grubbs criterion

The results of checking the studies for the presence of emissions and quasi-emissions according to the Grubbs criterion are shown in Fig. 9.

In an experimental study with the presence of an automatic water fire extinguishing system in the protective structure, a certain decrease in temperature is observed after 200 seconds of observation, which is explained by the cooling of the building structures of the protective structure by water flows. Therefore, for further substantiation of the temperature regime during a fire on transformers located inside a protective structure, the condition for the most severe effect of temperature on building structures should be accepted. That is, when there is no automatic fire extinguishing system in the premises of the protective structure. It is appropriate to take into account only the readings of temperature sensors, which are located at the level of 18 m from the floor level of the protective structure.



a



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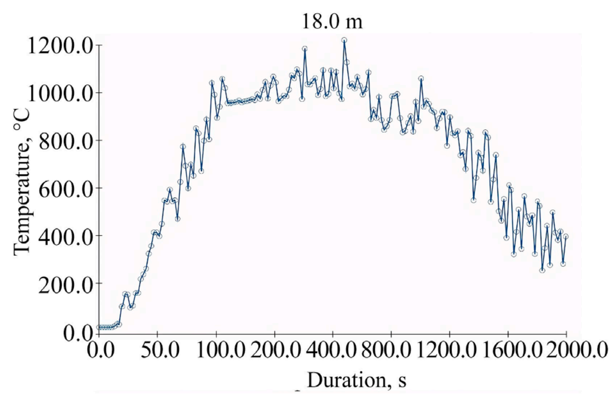

c

Fig. 7. Dynamics of temperature changes in the protective structure during the burning of the autotransformer according to the data from a temperature sensor installed at heights of 1 m, 10 m, 18 m above the site of the fire, when the protective structure has an automatic water fire extinguishing system: *a* – for the installation level of temperature sensors of 1 m; *b* – for the installation level of temperature sensors of 10 m; *c* – for the installation level of temperature sensors of 18 m

Fig. 10 shows the averaged temperature curve based on the results of the conducted research from readings of thermocouple sensors. They are located at the level of 18 m from the floor level of the protective structure, where the transformer is arranged in case the room of the protective structure is not equipped with an automatic water fire extinguishing system. The temperature curve of a fire under the conditions defined above, which is obtained by the calculation method, in comparison with the standardized temperature curves for a hydrocarbon fire and a standard fire temperature regime.

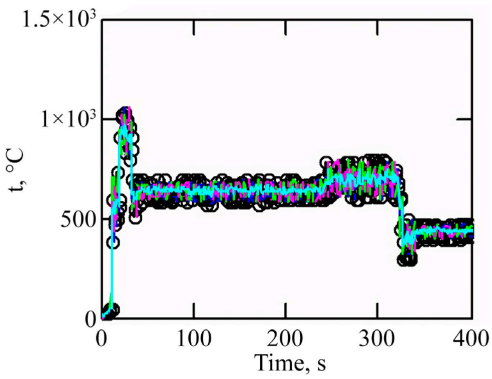

Fig. 8. Dynamics of temperature changes in the protective structure during the burning of the autotransformer according to the data from temperature sensors installed at a height of 18 m above the site of combustion, when the protective structure does not have an automatic water extinguishing system

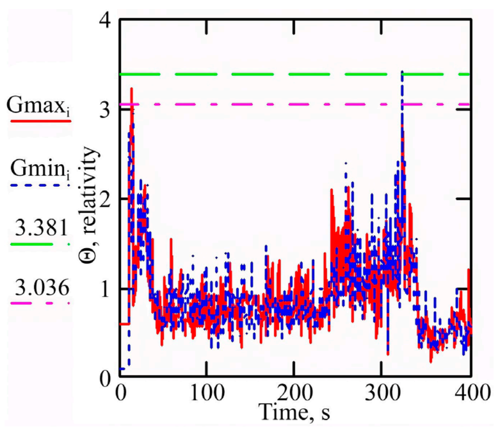

Fig. 9. Results of checking the studies for the presence of emissions and quasi-emissions according to the Grubbs criterion

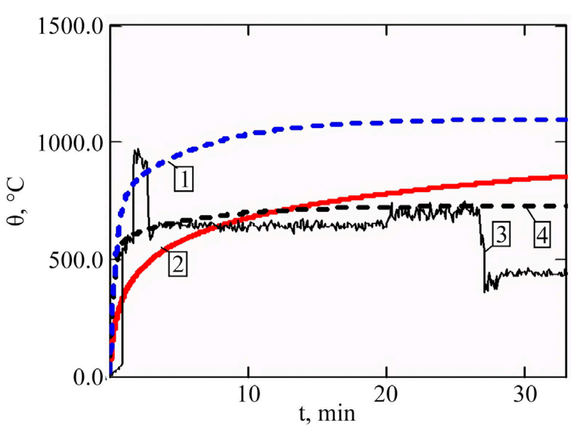

Fig. 10. Temperature curves of fire modes: 1 – hydrocarbon temperature mode of fire; 2 – standard fire temperature regime; 3 – the temperature curve of the fire mode, obtained by the calculation method; 4 – modified hydrocarbon temperature mode of fire

Given that the hydrocarbon temperature regime of a fire follows the following dependence [16]:

$$\theta_p(t)=1{,}080\,(1-0.325\,e^{-0.167t}-0.675e^{-2.5t})+\theta_0, \qquad (1)$$

where t is the time of a standard fire test, s;

θ_0 is the initial temperature of the environment, °C; $\theta_0 \approx 20$ °C;

$\theta_p(t)$ is the temperature in the fire chamber of the device for determining limits.

The standard fire temperature regime obeys the following dependence according to [16]:

$$\theta_p(t)=345\cdot\lg(8t/60+1)+\theta_0. \qquad (2)$$

Thus, in order to derive the equation that characterizes the hydrocarbon temperature regime of a fire on a transformer installed inside a protective structure, taking into account the most significant factors of fire spread and the conditions of its development, it was decided to take as a basis equations (1), (2) and modify them based on of the resulting dependences shown in the plots (Fig. 8, 10).

5. 3. Substantiation of the modified temperature regime during a fire on a transformer placed inside a protective structure

Based on the data from the temperature change dynamics shown in the plot (Fig. 8), the modified hydrocarbon temperature regime of the fire during the burning of the transformer, which is located inside the protective structure, can be determined from the dependence:

$$\theta_p(t)=680\,(1-0.325\,e^{-0.967t}-0.675e^{-2.5t})+\theta_0. \qquad (3)$$

This dependence simulates the initial sharp increase in temperature, which gradually stabilizes when the temperature reaches the limit value. Exponential terms indicate different rates of cooling or attenuation of the intensity of temperature growth.

6. Discussion of results of substantiating the parametric temperature regime during a fire on transformers

Significantly overestimated calculated heat loads on building structures, laid down as part of the implementation of the "Country – Fortress" Concept and approved by the resolution of the Cabinet of Ministers of Ukraine dated April 26, 2024. No. 471 do not have proper scientific substantiation. This, in turn, unjustifiably increases the cost of design and estimate documentation and construction work during the construction of such objects, which is especially unacceptable under the conditions of a full-scale war.

Standardized temperature regimes are an important tool for evaluating fire resistance classes of building protective structures, enabling comparison of results, and ensuring reliability in their evaluation. The test temperature of building structures used at energy industry facilities has higher values than the regime shown in Fig. 4–7 than when testing the types of structures used in the public construction sector. In this case, the hydrocarbon temperature regime is used (Fig. 1). The data of Fig. 8 confirm the adequacy of the proposed modified hydrocarbon fire regime described by equation (3) based on the data of the temperature dependence curve (Fig. 8).

Special requirements for the fire resistance of the protective structures of the transformer premises under the conditions of the russian threat lead to the expectation of different consequences of the fire, which led to the consideration of two scenarios of the occurrence and spread of transformer fires. Temperature changes in the protective structure during the burning of the transformer were carried out according to the data from temperature sensors installed at heights of 1 m, 10 m, and 18 m above the place of combustion, when the protective structure has and does not have an automatic water fire extinguishing system. The study confirms that it is advisable to take the location of the sensors at the level of 18 m from the floor level and the absence of a protective structure of the automatic fire extinguishing system in the room as a condition for the most severe impact of temperature (Fig. 10). This choice is due to the largest value of the temperature regime, which was observed for the applied group of temperature sensors.

According to the results of the averaged temperature curve of the fire regime, obtained by the calculation method, it is possible to note a decrease in the combustion temperature after 30 minutes of fire, which can be explained by the burnout of the fire load. Also, it is advisable to use this temperature regime to justify the standardized fire resistance class of the enclosing structures of protective structures in which transformers are installed, taking into account the reserve factor of 1.2, which should be at least REI 45.

In contrast to existing hydrocarbon fire regime, our results regarding the modified temperature regime make it possible to establish the minimum necessary requirements for the building protective structures of transformers, taking into account the parametric approach. This makes it possible to take into account the real fire load and conditions of thermal impact on building structures. The modified temperature regime with a parametric approach makes it possible not only to increase the reliability of building structures but also optimize resources and costs, which is important for effective fire safety management. The parametric approach takes into account ideal conditions and typical scenarios but in real operation, non-standard situations may arise that are difficult to predict. Results of the study relate to certain classes of transformers (AT 330 kV and AT 750 kV), so they cannot always be applied to others without additional adjustments. These limitations require further research and verification in order to adapt the results for practical application and improve the accuracy of the established requirements for protective structures.

As a result, the temperature regime during a fire of a transformer located inside a protective structure was calculated according to a field model, using the reaction of simple stoichiometry. This became the basis for further calculation of fire scenarios and modeling of its potential impact for protective transformer structures. However, the study took into account only normal operating conditions since existing computer model does not foresee the application of conditions associated with the destructive factors of Russian armed aggression.

Our results are based only on theoretical studies. Dependence on the initial conditions indicates that the parametric approach requires advancing the research to ensure its effectiveness and reliability under various operating conditions. In further studies, it is advisable to test the model built and confirm the adequacy of our results.

7. Conclusions

1. Starting conditions for the calculation scenario of the fire of transformers in building protective structures have been determined. The scenarios of the occurrence and development of the fire, which involve an emergency spill of transformer oil in the closed volume of the room, which performs the function of a protective structure, have been substantiated.

2. Based on the generalized and systematized mathematical models, computer simulation was carried out, which made it possible to obtain data for calculating the modified temperature regime of a fire on a transformer that can occur in the volume of a protective structure.

3. We have substantiated the modified hydrocarbon temperature mode of fire during the burning of the transformer, which is located inside the protective structure, and which can be determined through the empirical dependence of temperature change over time. The proposed relationship describing the temperature regime for this type of building, in the event of a fire, takes into account the increase in the maximum temperature value to 1100 °C during 30 minutes of fire. In this case, the nature of the temperature curve has a more pronounced extremum during the first three minutes of the fire, in contrast to an existing hydrocarbon fire regime.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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