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RESEARCH ON THE IMPACT OF DIESEL GENERATOR FIRE ON BUILDING STRUCTURES OF ENCLOSED SPACES

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The work established the spatial-temporal dependencies of the change in the temperature regime of a diesel generator fire in a closed room depending on the height and distance from the combustion center, and also determined critical temperature ranges for different zones of the room. Quantitative dependencies of thermal loads on enclosing and supporting structures on the diesel fuel combustion scenario were obtained, which allow predicting the loss of fire resistance of structures and justifying the requirements for their fire resistance class and fire zoning of generator station premises. As a result of the conducted numerical and full-scale fire studies, it was established that fires of diesel generator sets in closed rooms are characterized by rapid development and formation of critical temperature regimes, capable of leading to the loss of the bearing capacity of building structures in a short time. The obtained results confirm the feasibility of using computer modeling together with experimental studies for the scientific substantiation of fire safety requirements and fire resistance of generator station premises in buildings of various functional purposes.

Keywords: temperature regime of fire, generator sets, fire resistance of structures, fire safety, computer modeling, integrity of structures.

Introduction. Ensuring backup and emergency power supply for buildings of various functional purposes is a critical component of maintaining everyday human activity. As recently as five years ago, the installation of individual generator units in residential, public, and administrative buildings was considered a highly unlikely exception, typically associated with emergencies resulting from technological or natural disasters that could cause power outages. At that time, Ukraine's well-developed and robust energy sector ensured stable and reliable electricity supply for consumers, fully meeting the needs of industry, the social sector, and the population, while also creating significant export potential. With the onset of the full-scale war in Ukraine, which necessitated adjustments, rapid adaptation and reorientation toward more resilient and autonomous energy sources, the use of individual generator units of various types became widespread and, in practice, a largely non-alternative solution for ensuring uninterrupted power supply to critical infrastructure facilities, as well as residential, public, and administrative buildings.

According to data from the State Customs Service of Ukraine, nearly 1,000,000 electric generators were imported into Ukraine during 2022-2023, with annual import volumes since 2022 ranging between USD 0.75 and 1.5 billion [1].

Simultaneously with the process of ensuring energy autonomy, the number of fires caused by violations of generator operating rules and non-compliance with fire safety requirements has increased. This situation is largely attributable to the absence of clearly defined building regulations governing the arrangement of spaces for generator installations assigned for emergency and backup power supply in buildings and structures. In addition, during the design of new buildings or generator station

premises, structural designers lack reliable data on actual potential hazards and the thermal regimes of fires that may occur in such premises, particularly with respect to ensuring the structural integrity and fire resistance of building components under fire conditions.

It should be noted that in 2022, specialists of the State Emergency Service of Ukraine promptly developed recommendations for household generator use and introduced amendments to the Fire Safety Rules of Ukraine [2], addressing household generators with a capacity of up to 20 kW and fuel tank volumes of up to 100 L. However, regulatory provisions concerning building regulations for generator station premises of higher-capacity in buildings and structures of various functional purposes remain unresolved.

In this context, the key issue in ensuring compliance with building regulations in terms of fire safety is the creation of conditions that preserve the load-bearing capacity of structures and limit fire ignition and spread [3].

Consequently, to develop well-founded building regulations for the placement of electric generators, it became necessary to provide a scientific justification for fire protection requirements related to spatial and planning solutions for facilities housing power-generating equipment, particularly diesel generator units.

The presented studies of fires involving diesel generator units in enclosed spaces include a comprehensive assessment of fire development characteristics under confined conditions, aimed at evaluating internal temperature regimes and the impact of fire propagation through open apertures on adjacent structures. Prior to conducting full-scale fire experiments, computer modeling of an emergency scenario was performed to preliminarily assess expected outcomes, identify critical thermal loads on building structures, and verify the layout of measurement equipment.

Review of publications. Numerous researchers have addressed the substantiation of fire safety requirements for buildings and structures containing energy and generator installations. In particular, study [4] investigated temperature variations during transformer fires located within protective structures, enabling evaluation of fire temperature regimes and justification of the minimum fire resistance class for protective structures under modified thermal conditions. However, this study lacks full-scale fire experiments necessary for comprehensive verification of the obtained results. Studies [5] provide a thorough examination of heating and failure mechanisms of glazing in translucent building envelope elements under standard fire temperature conditions, as well as the fire resistance of reinforced concrete structures to ensure building occupant safety. Nevertheless, these studies do not consider generator units as primary fire sources, nor diesel fuel as the main fire load, and do not investigate the spread of hazardous fire factors to adjacent objects through glazed openings.

Study [6] presents an analysis of potential accident consequences resulting from generator fires on offshore platforms using computer modeling, demonstrating risks to equipment, structures, and overall structural safety. While the study identifies important factors influencing fire development in generator installations, its results cannot be fully extrapolated to substantiate structural requirements for generator station premises within buildings.

At the same time, to optimize testing processes and reduce environmental impact, alternative methods for assessing fire effects on building structures are being actively developed. In particular, study [7] proposes and substantiates an environmentally safe compact testing facility using electric heating elements instead of liquid fuel. This equipment is capable of reproducing heating regimes to assess the fire resistance of small structural fragments and the effectiveness of fire-retardant coatings. However, despite the practical value of such localized tests, full-scale fire experiments remain critically necessary for a comprehensive understanding of thermodynamic processes and integrated thermal impacts resulting from real diesel generator fires in enclosed spaces.

Thus, conducting full-scale fire experiments and computer modeling to determine critical thermal loads on building structures during fires involving diesel generator units in enclosed spaces constitutes a relevant scientific problem in the field of construction industry.

Formulation of research purpose. The objective of this study is to determine the characteristics of fire development within a diesel generator station premise through a comprehensive investigation of fire development processes under confined conditions.

Methods and Research Results. The methodology for full-scale fire experiments to assess the fire temperature regime in an enclosed generator station room (hereinafter referred to as the Methodology)

applies to studies aimed at evaluating the dynamics of temperature changes within a diesel electric generator station (DEGS) during combustion of a diesel generator with a fuel tank volume of up to 200 L. In addition, it is planned to determine the potential thermal effects on external enclosing structures (constructed of concrete blocks) of the DEGS premises in order to establish substantiated requirements for their minimum required fire resistance class.

During testing, a full-scale mock-up of a diesel electric generator is installed within a room simulating a typical DEGS configuration. A model fire source simulating fuel spillage from the generator fuel tank is arranged to reproduce thermal impacts comparable to real combustion conditions for generators of the specified capacity and fuel volume. These conditions allow the experimental setup to closely approximate a real fire scenario.

Fire temperature measurements were performed using a data acquisition and processing system comprising an analog input module for thermocouple signal acquisition with a sampling interval of one second. The system provides automatic real-time data recording, preliminary processing, visualization, and archiving. Prior to testing, data acquisition channels were calibrated and thermocouple connections verified. Temperature recording commenced simultaneously with fire ignition.

Figure 1 presents a schematic layout of the simulated diesel generator mock-up, the Class B model fire source (377 B), type K thermocouple locations within the test chamber, and photographs of the full-scale experimental setup.

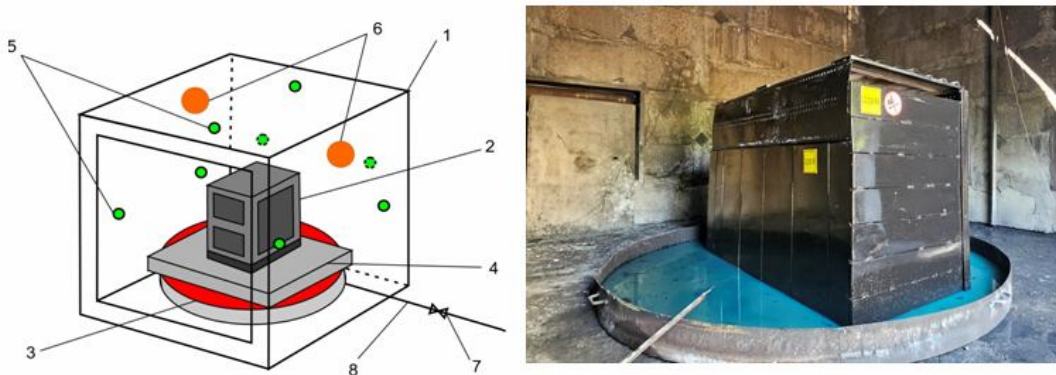


Fig. 1. Schematic layout of the fire test chamber with the installed mock-up, Class B model fire source (377 B), and measuring equipment, where: 1 – fire test chamber; 2 – full-scale mock-up of a 150 kW diesel electric generator; 3 – Class B model fire source (377 B); 4 – reinforced concrete mounting slab; 5 – Type K thermocouples installed within the fire chamber volume; 6 – fire suppression modules; 7 – fuel drainage shut-off valve; 8 – fuel supply pipe

Each test configuration was conducted no fewer than three times for each type of generator mock-up and model fire source. Upon completion of the experiments, the obtained data were recorded in primary data protocols.

To determine the degree of dispersion of the values of a random variable (x_i) relative to its mathematical expectation (\bar{x}_i) and the variability of the sample, the standard deviation of the research results was calculated using Equation (1) [8, 9]:

$$S = \sqrt{\frac{\sum_{i=1}^n |x_i - \bar{x}_i|^2}{n}}. \quad (1)$$

To determine the average deviations of the i^{th} study's value from the mean of all studies, the average absolute deviation was calculated using Equation (2) [8, 9]:

$$d = \frac{\sum_{i=1}^n |x_i - \bar{x}_i|}{n}. \quad (2)$$

The average relative deviation was determined using the following Equation (3) [8, 9] to express linear deviations as percentages and to enhance the informativeness of the analysis:

$$b = \frac{\sum_{i=1}^n |x_i - \bar{x}_i|}{n \cdot \bar{x}_i} \cdot 100\%. \quad (3)$$

The significance of the smallest value deviation in the ordered data set $y_{j\min}$ was evaluated using the Grubbs criterion $G_{j\min}$ according to Equation (4) [8, 9]:

$$G_{j\min} = \frac{\bar{y}_i - y_{j\min}}{S_i}. \quad (4)$$

With calculated values $G_{j\max}$ and $G_{j\min}$ compared to the 5% ($G_{\text{crit. } 5\%}$) and 1% ($G_{\text{crit. } 1\%}$) critical thresholds, given in tables [8, 9] for three measurements (1,715 and 1,764).

Prior to conducting full-scale fire experiments, computer modeling of the accident scenario was performed to preliminarily assess expected outcomes, identify critical thermal loads on building structures, and verify the measurement system layout. The Fire Dynamics Simulator (FDS) software package was selected as the modeling tool, implementing computational fluid dynamics (CFD). The mathematical model is based on the numerical solution of the Navier-Stokes equations for low-speed, temperature-dependent flows, enabling detailed spatial and temporal description of heat and mass transfer processes [10, 11].

According to the selected fire scenario, fire development within the room reaches its maximum area throughout the entire simulation duration (15 minutes). This duration also corresponds to the standard response time of fire and rescue units, including deployment operations.

To obtain thermodynamic environment data, an array of virtual thermocouples (sensors) was employed using a vertical zoning scheme. Sensor heights of 0.5 m, 3.5 m, and 5.5 m were selected around the room perimeter and at the center of the fire source. The fire source area was 10 m², and the computational grid resolution was set at 0.25 m. The computer model of the fire test chamber is shown in Figure 2.

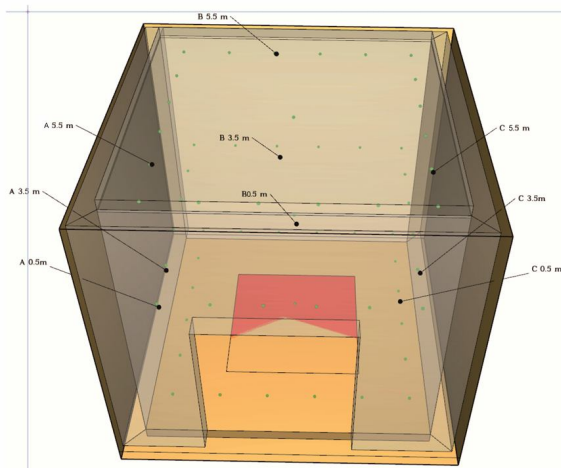


Fig. 2. Three-dimensional model of the fire test chamber with the layout of temperature sensors

During the modeling of combustion involving a spill of 200 L of diesel fuel, the obtained results demonstrate a high intensity of fire development and a severe thermal regime. In the zone of direct combustion (the center of the fire source), high-amplitude turbulent temperature fluctuations were recorded, with peak values in the range of 850-950°C and an averaged temperature of approximately 560-580°C.

Figure 3 presents the obtained temperature-time curves for the investigated fire test chamber.

In the ceiling zone of the fire test chamber (at a height of 5.5 m), temperatures reached 640-800°C, which may potentially result in critical thermal effects on the load-bearing elements of the floor slab. The corresponding temperature profiles for this zone are shown in Figure 4.

In the middle zone of the fire test chamber walls (at a height of 3.5 m), temperatures in the range of 420-510°C were recorded. This temperature distribution is primarily attributable to the mixing processes of hot combustion gases with the surrounding air. The corresponding graphs are presented in Figure 5.

At a level of 0.5 m above the floor, temperature values ranged from 340 to 540°C. Heating in this zone occurs predominantly due to intense thermal radiation from the flame plume, as convective heat transfer is limited by the inflow of cooler air toward the combustion zone. This behavior is illustrated by the graph in Figure 6.

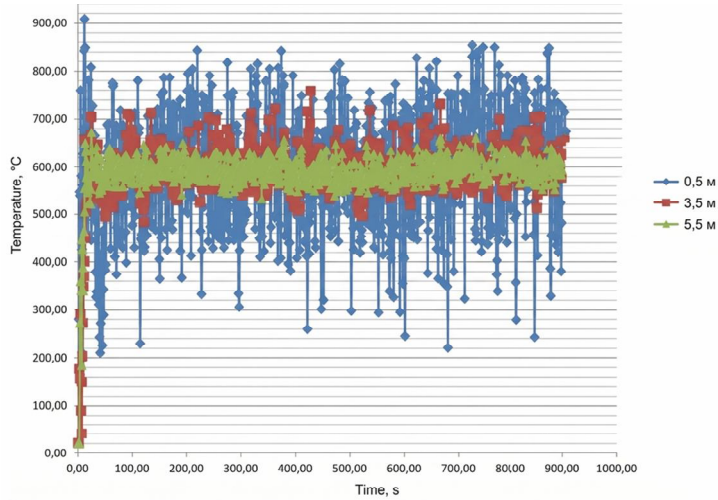


Fig. 3. Temperature readings of sensors located at the center of the fire source at heights of 0.5 m, 3.5 m, and 5.5 m



Fig. 4. Temperature readings of sensors along the perimeter of the fire test chamber walls at a height of 5.5 m (sensor layout according to the scheme in Fig. 2)

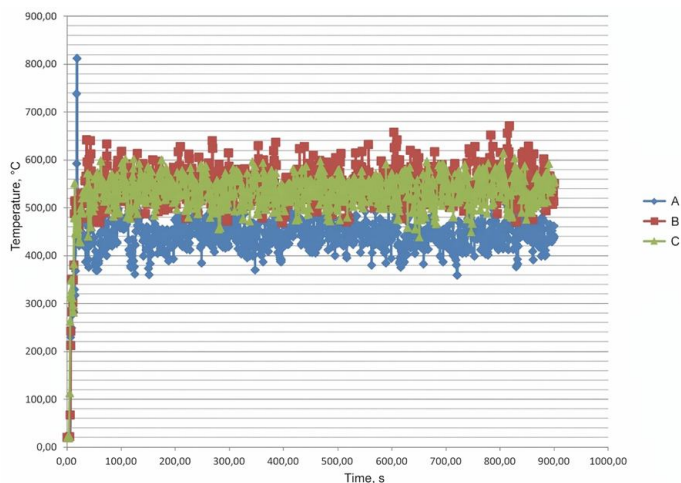


Fig. 5. Temperature readings of sensors along the perimeter of the fire test chamber walls at a height of 3.5 m (sensor layout according to the scheme in Fig. 2)

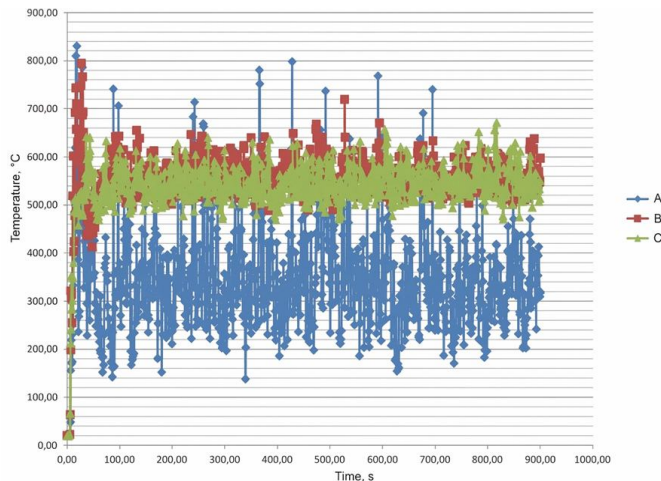


Fig. 6. Temperature readings of sensors located along the perimeter of the fire test chamber walls at a height of 0.5 m (sensor layout according to the scheme in Fig. 2)

In addition, the numerical modeling yielded a thermal map of the internal wall surfaces, revealing a markedly non-uniform temperature distribution that varies significantly with height. The primary thermal load is concentrated in the upper portions of the fire test chamber walls and the ceiling, where, according to the color scale, temperatures reach critical values of up to 770°C. This phenomenon is caused by the accumulation of overheated combustion products beneath the ceiling and intense thermal radiation from the open flame. The images clearly indicate zones of local overheating in the vicinity of the fire source. At the same time, the lower sections of the walls, approximately up to a height of 1.5-2.0 m, remain within a relatively cooler zone due to the continuous inflow of fresh air, as evidenced by the cooler color spectrum in the lower part of the model, shown in Figure 7.

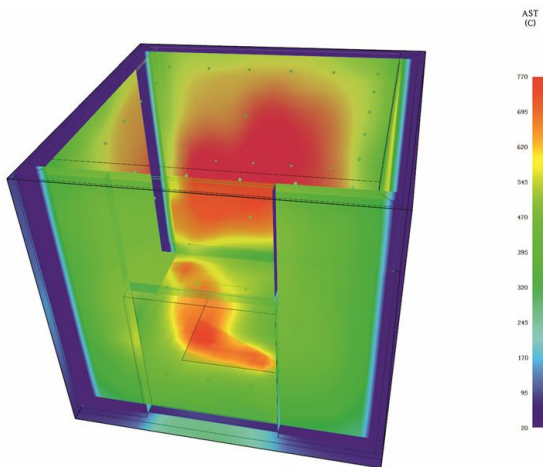


Fig. 7. Temperature distribution on the internal wall surfaces of the building

Based on the results of the numerical modeling, a forecast of the fire temperature development and thermal load levels in various zones of the fire test chamber was performed. These data made it possible to identify critical heights, characteristic temperature ranges, and the most hazardous zones, which is essential for substantiating safety conditions and selecting appropriate parameters for the measurement equipment. This forecasting formed the basis for the organization and

execution of full-scale fire experiments, taking into account the expected thermal impacts and the anticipated fire development scenario.

Figure 8 shows one of the full-scale fire experiments conducted to assess the fire temperature regime in an enclosed generator room in accordance with the Methodology.

A series of full-scale fire experiments demonstrated that, during the combustion of the specified amount of fuel, a stable temperature regime in the gaseous environment was observed at a level of 480-550°C. This temperature range slightly exceeds the critical exposure temperature for unprotected steel elements (500°C) [12], at which a loss of load-bearing capacity may occur. As the temperature curves indicate that such a thermal regime is established almost immediately after ignition (within less than 60 seconds of free burning), structural elements may be subjected to a so-called “thermal shock”, resulting in significant thermal stresses and deformations even before the initiation of firefighting operations.

Figure 9 presents temperature profiles constructed on the basis of averaged values obtained from a series of three experimental tests.



Fig. 8. Conduct of a full-scale fire experiment

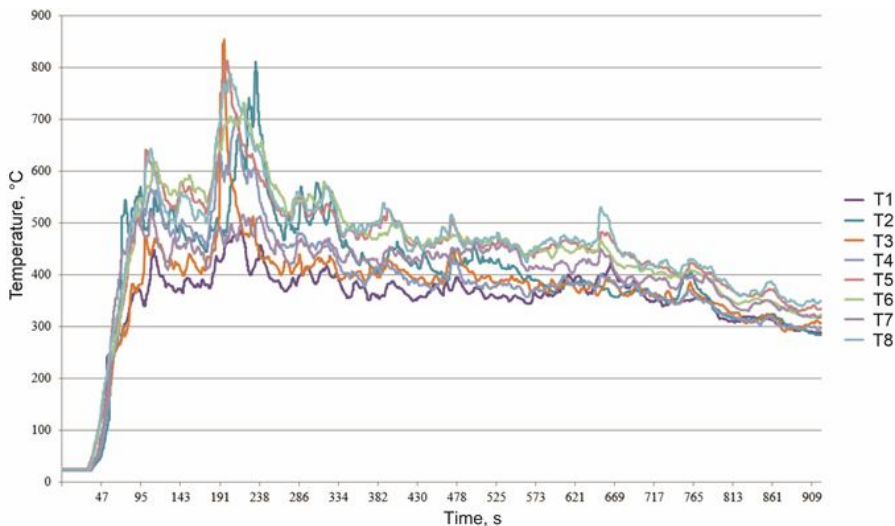


Fig. 9. Time history of temperature variation inside the generator station premise (T1-T8 denote temperature readings from thermocouples located within the fire test chamber volume, positioned according to the layout shown in Fig. 2)

The recorded temperature regime in the range of 640-700°C during the initial minutes of the fire may be critical for concrete structures and can lead to significant degradation of their physical and mechanical properties. At such temperatures, intensive deterioration of the cement matrix may occur due to the decomposition of hydrated compounds, which is accompanied by a sharp reduction in material strength and stiffness. Non-uniform thermal expansion of concrete constituents can induce the development of thermal stresses and cracking, while the presence of moisture (steam, including that generated during firefighting operations) may cause explosive spalling of surface layers. In reinforced concrete elements, additional degradation of the bond between concrete and reinforcement may be observed, which, combined with material strength loss, results in a substantial reduction in load-bearing capacity and operational reliability of the structures [13, 14].

For masonry structures, prolonged exposure to temperatures in the range of 500-550°C may also have adverse effects, although the masonry units themselves (ceramic, clinker bricks, etc.) generally exhibit high thermal resistance. The primary damage mechanism is associated with degradation of the mortar, which undergoes dehydration, cracking, and loss of strength significantly faster than the masonry units. Non-uniform heating of masonry can potentially lead to the development of internal stresses and microcracking in both bricks and joints; after cooling, this may result in increased porosity and reduced durability of the structure. Consequently, even in the absence of visually apparent

damage, irreversible structural deterioration may occur, significantly shortening service life and potentially necessitating strengthening or replacement of damaged elements [15, 16].

A comparison of the experimental data with the results of numerical modeling indicates that the overall characteristics of the temperature regime were predicted with sufficient accuracy. The reliability of the computational modeling is confirmed by the fact that the deviation between experimental and calculated temperature values ranged from 12 to 15 %, which falls within acceptable error limits for full-scale fire experiments of this magnitude.

Conclusions. With the onset of the full-scale war in Ukraine, the use of individual diesel generator units has become widespread and, in many cases, an almost non-alternative solution for ensuring uninterrupted power supply to residential, public, and administrative infrastructure facilities. The need for scientific substantiation of fire safety requirements is driven by the absence of comprehensive building regulations governing the placement and operation of generators, which significantly increases fire risks. The conducted study highlights the necessity of well-founded requirements for spatial and planning solutions of generator station premises in order to ensure structural integrity and stability under fire conditions.

The application of the Fire Dynamics Simulator (FDS) made it possible to assess the potential effects of flame development, hot gas turbulence, and thermal loads on enclosure structures. Critical temperatures of up to 850-950°C were identified at the center of the fire source, while temperatures of 640-800°C beneath the ceiling and 420-510°C along the walls were recorded. These results enabled the identification of hazardous zones that critically affect the load-bearing capacity of floor slabs and enclosure elements and may serve as a basis for substantiating the need for fire protection measures.

Experimental investigations confirmed that during the combustion of 200 L of diesel fuel, a stable gas-phase temperature regime of 480-550°C is established, with local peaks reaching 850-950°C. High heating rates (temperature peaks occurring in less than 60 s) create conditions of “thermal shock” for steel and reinforced concrete structures, potentially leading to loss of load-bearing capacity, thermal deformations, and cracking. For masonry structures, the critical factor is the degradation of mortar and the formation of microcracks, which reduce durability and increase the risk of structural damage.

Comparison of experimental and computational results demonstrated that the general characteristics of the temperature regime were accurately predicted. The deviation between measured and simulated values of 12-15% lies within acceptable limits for large-scale fire studies. This confirms the applicability of numerical modeling for predicting similar fire scenarios and for substantiating fire resistance classes of building structures, fire zoning strategies, and the selection of fire suppression system parameters in generator station premises.

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ДОСЛІДЖЕННЯ ВПЛИВУ ПОЖЕЖИ ДИЗЕЛЬНИХ ГЕНЕРАТОРНИХ УСТАНОВОК НА БУДІВЕЛЬНІ КОНСТРУКЦІЇ ЗАКРИТИХ ПРИМІЩЕНЬ

Актуальність. Порушення правил експлуатації та недооцінка реальних температурних режимів пожеж у приміщеннях генераторних станцій призводять до зростання пожежної небезпеки й ризику втрати несної здатності будівельних конструкцій. Недостатнє врахування реальних температурних режимів пожеж у приміщеннях дизельних генераторних станцій ускладнює забезпечення вогнестійкості та експлуатаційної надійності будівель і споруд. У зв'язку з цим постає необхідність науково обґрунтованого дослідження теплових впливів пожеж дизельних генераторів для формування ефективних і безпечних об'ємно-планувальних та конструктивних рішень. **Мета.** Дослідження характеру розвитку пожежі дизельної генераторної установки в умовах закритого приміщення шляхом поєднання чисельного моделювання та натурних вогневих випробувань для визначення критичних температурних режимів і теплових навантажень на будівельні конструкції з метою обґрунтування вимог пожежної безпеки приміщень генераторних станцій. **Основні результати.** У роботі експериментально та чисельно досліджено температурний режим пожежі дизельної генераторної установки в закритому приміщенні, встановлено критичні теплові навантаження та небезпечні зони, що можуть призводити до втрати несної здатності сталевих, залізобетонних і цегляних конструкцій. Порівняння результатів натурних вогневих досліджень і комп'ютерного моделювання у середовищі FDS показало їхню узгодженість з відхиленням 12-15 %, що підтверджує можливість використання чисельного моделювання для обґрунтування вимог вогнестійкості приміщень генераторних станцій. Встановлено просторово-часові залежності зміни температурного режиму пожежі дизельної генераторної установки в закритому приміщенні залежно від висоти та віддаленості від осередку горіння, а також визначено критичні температурні діапазони для різних зон приміщення. Отримано кількісні залежності теплових навантажень на огорожувальні та несні конструкції від сценарію горіння дизельного палива, що дозволяють прогнозувати втрату межі вогнестійкості конструкцій і обґрунтовувати вимоги до їх вогнезахисту та протипожежного зонування приміщень генераторних станцій. **Висновки.** У результаті проведених чисельних і натурних вогневих досліджень встановлено, що пожежі дизельних генераторних установок у закритих приміщеннях характеризуються швидким розвитком і формуванням критичних температурних режимів, здатних у короткий час призводити до втрати несної здатності будівельних конструкцій. Отримані результати підтверджують доцільність використання комп'ютерного моделювання спільно з експериментальними дослідженнями для наукового обґрунтування вимог пожежної безпеки та вогнестійкості будівельних конструкцій приміщень генераторних станцій у будівлях різного функціонального призначення.

Ключові слова: температурний режим пожежі, генераторні установки, вогнестійкість конструкцій, пожежна безпека, комп'ютерне моделювання, цілісність споруд.

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RESEARCH ON THE IMPACT OF DIESEL GENERATOR FIRE ON BUILDING STRUCTURES OF ENCLOSED SPACES

Actuality. Violation of operating rules and underestimation of real temperature regimes of fires in generator stations lead to an increase in fire hazard and the risk of loss of load-bearing capacity of building structures. Insufficient consideration of real temperature regimes of fires in diesel generator stations makes it difficult to ensure fire resistance and operational reliability of buildings and structures. In this regard, there is a need for scientifically substantiated research into the thermal effects of diesel generator fires to form effective and safe spatial planning and design solutions. **Purpose.** Study of the nature of the development of a diesel generator fire in a closed room by combining numerical modeling and full-scale fire tests to determine critical temperature regimes and thermal loads on building structures in order to substantiate the fire safety requirements of generator station premises. **Main results.** The work experimentally and numerically investigated the temperature regime of a diesel generator fire in a closed room, established critical thermal loads and dangerous zones that can lead to the loss of the bearing capacity of metal, reinforced concrete and brick structures. Comparison of the results of full-scale fire studies and computer modeling in the FDS environment showed their consistency with a deviation of 12-15%, which confirms the possibility of using

numerical modeling to substantiate the fire resistance requirements of generator station premises. Established the spatial-temporal dependencies of the change in the temperature regime of a diesel generator fire in a closed room depending on the height and distance from the combustion center, and also determined critical temperature ranges for different zones of the room. Quantitative dependencies of thermal loads on enclosing and supporting structures on the diesel fuel combustion scenario were obtained, which allow predicting the loss of fire resistance of structures and justifying the requirements for their fire resistance class and fire zoning of generator station premises. **Conclusions.** As a result of the conducted numerical and full-scale fire studies, it was established that fires of diesel generator sets in closed rooms are characterized by rapid development and formation of critical temperature regimes, capable of leading to the loss of the bearing capacity of building structures in a short time. The obtained results confirm the feasibility of using computer modeling together with experimental studies for the scientific substantiation of fire safety requirements and fire resistance of generator station premises in buildings of various functional purposes.

Keywords: temperature regime of fire, generator sets, fire resistance of structures, fire safety, computer modeling, integrity of structures.

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У роботі встановлено просторово-часові залежності зміни температурного режиму пожежі дизельної генераторної установки в закритому приміщенні залежно від висоти та віддаленості від осередку горіння, а також визначено критичні температурні діапазони, що здатні у короткий час призводити до втрати несної здатності будівельних конструкцій.

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This study establishes the spatial and temporal dependencies of the temperature regime of a fire in a diesel generator set located in an enclosed room, depending on the height and distance from the center of combustion, and identifies the critical temperature ranges capable of rapidly causing a loss of load-bearing capacity (fire resistance) in building structures.

Fig. 9. Ref. 16.

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