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Development of a Method for Increasing the Fire Resistance of Cast-iron Structures of Cultural Heritage Sites under Reconstruction

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Abstract

When reconstructing cultural heritage sites, significant changes to the original design planning are not allowed. More rational methods are needed to increase the fire resistance of historical buildings, which will ensure their fire safety and preserve their architectural value. Nowadays, most heritage sites do not meet the safety requirements of modern buildings. The purpose of the study is to develop a methodology for increasing the fire resistance of cast iron structures. The key tasks are increasing the fire resistance of buildings during reconstruction and ensuring their fire safety during operation. The tasks have been achieved by developing a new methodology for increasing the fire resistance of cast iron. It includes an integrated approach to assessing the risk of a fire, a predictive model for the occurrence of fire danger, as well as various scenarios for the fire development caused by cast iron heating. The results' analysis has allowed us to determine the fire resistance limits of cast iron structures. The scientific novelty lies in the study of the fire resistance of cast iron structures using a three-dimensional mathematical model. The resulting values have been obtained via differential equations of the laws of mass conservation, momentum, gaseous energy, and the optical density of smoke.

Keywords: Cultural Heritage Objects; Building Reconstruction; Building Structures Fire Resistance; Heat Transfer; Fire Resistance Limit; Outbreak of Gasification Products; Fire-Fighting Structural Elements; Modeling of Thermogasdynamics of a Building Fire.

1. Introduction

The purpose of the work is to develop a method for determining and increasing the fire resistance of cast iron structures of a cultural heritage object based on mathematical modeling of the thermogasdynamics of a fire. The problem of the study comes from the fact that during the reconstruction or overhaul of cultural heritage sites, rational and effective methods are required to increase the fire resistance of building structures and ensure the fire safety of objects during further operation. In addition, the methods being developed to increase the fire resistance of building structures should not lead to significant changes in architectural, structural, and spatial planning solutions for buildings. The object of the

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study is the pattern of changes in the fire resistance of cast-iron structures in the historical building "Tsar Grad Hotel" in the city of Yaroslavl. The characteristics of the research object are presented in Chapter 2. The relevance of the work is related to the fact that during the reconstruction of cultural heritage sites, rational methods are needed to increase the fire resistance of building structures that will effectively ensure the fire safety of the building and preserve the historical and architectural value of the object.

The scientific novelty lies in the study of the fire resistance of cast-iron structures using a three-dimensional mathematical model of fire thermogasdynamics. It should be noted that three-dimensional models are mainly used for modeling the evacuation of people from a fire zone. In this study, a 3D model is used to simulate the behavior of cast iron structures, which is a new approach. Based on the calculation of a 3D mathematical model of the fire scenario, a scientific approach (methodology) to increase the fire resistance of load-bearing cast iron building structures is justified.

The experimental part of the study includes an assessment of the fire resistance limits of load-bearing cast iron structural elements of structures. For this purpose, 3D mathematical models have been developed, and numerical calculations of the dynamics of fire development have been performed. It has been theoretically established and experimentally proven that the actual fire resistance limit of a cast iron element with a minimum reduced metal thickness is less than the required fire resistance limit. The results obtained make it possible to develop rational measures that will ensure fire safety and preserve the historical appearance of the object. The practical significance of the research results lies in the development and implementation of a method for increasing the fire resistance of building structures during the reconstruction of cultural heritage sites.

Buildings and structures that belong to cultural heritage sites, as a rule, do not comply with modern standards in construction, including fire safety requirements, as analyzed by Lisienkova et al. (2021) [1], Garcia-Castillo et al. (2023) [2], and Salazar et al. (2021) [3]. Therefore, when reconstructing or overhauling (restoring) cultural heritage sites, it is necessary to develop special design solutions and fire-fighting measures to ensure building codes and established fire resistance limits of building structures. However, design solutions and firefighting measures specially developed for each object should not lead to a significant change in the architectural, structural, and space-planning solutions of the premises of a building or structure, as shown by Gales et al. (2022) [4] and Arandelovic & Musil (2023) [5].

The purpose of the work is to determine the fire resistance of cast iron structures of marches and staircases at the cultural heritage site using the example of the reconstruction of the Tsar Grad Hotel 3, located in Yaroslavl, using mathematical modeling of fire thermogasdynamics. Garcia-Castillo et al. (2023) [2] present an analysis of the problem of compliance of cultural heritage buildings with modern fire safety standards, subject to the preservation of historical space planning and design solutions. Salazar et al. (2021) [3], Gales et al. (2022) [4], Arandelovic & Musil (2023) [5], and a number of other authors have pointed out the difficulties of ensuring the fire resistance of building structures without significantly changing their parameters and placement in space, which leads to the loss of the historical and cultural value of the object.

Garcia-Castillo et al. (2023) [2], Arandelovic & Musil (2023) [5], Salihu et al. (2023) [6], and Song et al. (2021) [7] and studies by other authors indicate that there are no fire safety systems in buildings of cultural and historical heritage, as well as smoke extraction and automatic fire extinguishing systems. Therefore, assessing the fire risk for people in these facilities is a difficult and responsible task that depends on the design and other parameters of a particular facility. Shih et al. (2023) [8], Hou et al. (2021) [9], Shaham & Benenson. (2018) [10], Deng et al. (2022) [11], and Hvozd et al. (2021) [12] revealed that the determination of the level of fire safety should be carried out for the conditions of free development of the fire. However, in addition to ensuring the safe evacuation of people, it is also necessary to ensure the regulatory limits of fire resistance of building structures.

Garcia-Castillo et al. (2023) [2] showed that most of the studies were conducted for buildings made of wooden and steel structures. Fire hazard assessment in historical buildings with cast-iron structures was practically not carried out. The behavior of cast iron structures in fire conditions has not been sufficiently studied. Porter et al. (1998) [13] proposed measures to increase the fire resistance of cast iron structures at cultural heritage sites. The author proposed applying a fire-retardant layer of mineral wool to the surface of the structure. In this case, the effectiveness of fire protection is determined experimentally under the conditions of a “standard” fire.

However, there is currently no method for evaluating the behavior of cast-iron structures using mathematical modeling of the dynamics of a real fire. The development of such a method will allow for considering specific spatial planning solutions for premises and the properties of combustible materials contained in them. Therefore, the study of the actual fire resistance limits of cast iron building structures is relevant, has scientific novelty, and has practical interest. The authors of this work propose a method for mathematical modeling of a dangerous scenario of fire development. The method will allow a comprehensive assessment of the fire safety level of the cultural heritage site during reconstruction. Based on the assessment of the fire safety of the facility, the necessary fire-fighting measures will be developed to ensure the preservation of the historical value of the reconstruction facility.

When developing projects for the reconstruction of historical buildings and structures, a thorough analysis of the fire danger of objects is required in accordance with regulatory documents. For this purpose, calculated scenarios based on the ratio of time parameters of the development and spread of fire hazards can be used from the works Salihu et al.

(2023) [6], Song et al. (2021) [7], Shih & Tsai (2023) [8], and Hou et al. (2021) [9]. Calculation and modeling of probable scenarios for the development of a fire at a cultural heritage site will allow us to determine the risk to people and structures of objects and select the most effective fire protection systems for building structures from such works as Hou et al. (2021) [9], Shaham & Benenson (2018) [10], and Deng et al. (2022) [11].

In accordance with paragraph 2 of Article 35 of the Federal Law of the Russian Federation No. 123, "Technical Regulations on Fire Safety Requirements," the onset of fire resistance limits of load-bearing and enclosing building structures can be determined as a result of calculations. Therefore, when determining the building structure's fire resistance, the issue of the accuracy and reliability of the method of calculating heat and mass transfer in case of fire is key. Hvozd et al. (2021) [12] proposed that the complexity of implementing such a method lies in the multifactorial and non-linear nature of the problem. In addition, in accordance with clause 6.1 of the State Standard 30247.0-94, "Construction structures. Fire resistance test methods. General requirements": during testing, a temperature regime can be created that considers the actual conditions of fire development in a particular building [13].

During the reconstruction of cultural heritage sites, the problem arises from non-compliance of the actual values of the fire resistance limit of load-bearing and non-load-bearing structures of buildings with the current regulatory requirements and regulations. This is because the limit values of structures for fire resistance established in the current regulations in the field of construction of modern buildings are more stringent than the values of fire resistance limits at the time of construction of cultural heritage sites, as shown by Lisienkova et al. (2021) [1]. Kincaid (2019) [14] showed that the discrepancy between modern requirements for building structures fire resistance and the actual values of the fire resistance limits of structures at cultural heritage sites causes great difficulties in the reconstruction of such facilities.

Huang et al. (2011) [15], Hoffstaeter et al. (2023) [16], Maraveas et al. (2015) [17], and Lacaze et al. (2021) [18] showed a particularly difficult case during reconstruction is the increase in the actual fire resistance limits of building structures made of materials that are rarely used in modern construction. Such materials include, among others, cast-iron, which differs significantly in properties from steel. Maraveas et al. (2015) [17] noted that cast-iron structures were widely used in buildings of the past century. For example, very often the design solutions of cultural heritage sites of the 19th and 20th centuries assumed the presence of cast-iron stairs, as Kwasek & Piwek (2016) [19] showed.

To increase the building’s reliability, a variety of methods are used, which depend on the type of structure, the materials used, the wear degree, and other factors.

To increase the actual fire resistance limits of building structures to the required limits, various methods of constructive fire protection are currently used, as Mróz et al. (2016) [20]. For example, steel structures can be treated with bulging flame retardants, or an additional layer of heat-resistant material with a low coefficient of thermal conductivity (for example, mineral wool slabs) can be applied to the surface. There are also many known ways to increase reliability, including the fire resistance of wooden and other structures by Mróz et al. (2016) [20], Buchanan (2015) [21], Gravit et al. (2023) [22], and Golikov et al. (2016) [23]. There are currently no certified flame-retardant swelling compounds or other rational methods for cast-iron structures.

The issue of determining the actual fire resistance limit of cast-iron structures remains unresolved to date. This state of the issue is due to the fact that existing methods of testing structures for fire resistance that were proposed by Xiao Bin Huang et al. (2011) [15], Hoffstaeter et al. (2023) [16], Maraveas et al. (2015) [17], and Kodur et al. (2020) [24] do not take into account the specific features of cast-iron as a structural material, and there are no methods for calculating the actual fire resistance limit. Kodur et al. (2020) [24] reveal the results of the first half of the 20th century work and show that cast-iron structures lose strength to a lesser extent than steel structures when heated. The load-bearing capacity of the wrought iron at 550°C decreases by 60%. Cast-iron is more stable; to reduce its ability to withstand the load to the same extent (by 60%), exposure to a temperature of 700°C is required. Golikov et al. (2016) [23] proposed a method for fire protection of cast-iron structures using fire-resistant mineral wool plates. However, an important task is to preserve the original appearance of structures (for example, cast-iron stairs) in cultural heritage sites analyzed by Lisienkova et al. (2021) [1] and Mróz et al. (2016) [20].

Based on the above, increasing the actual fire resistance limits of cast-iron stairs must be carried out using fire-fighting measures that do not affect their appearance. To develop such measures, it is necessary to carry out mathematical modeling of the most dangerous scenarios at cultural heritage sites. The analysis of the results of numerical experiments will make it possible to develop fire-fighting measures that do not affect the appearance of structures and increase the actual fire resistance limits of the required ones.

In this paper, the fire resistance of cast-iron structures at cultural heritage sites is investigated, and a method for ensuring the fire resistance of load-bearing structures during the reconstruction of the studied objects is developed. The study of the fire resistance of cast-iron structures is based on mathematical modeling of fire thermogasdynamics. During the modeling, non-stationary three-dimensional differential equations of the laws of conservation of mass, momentum, and energy for the gaseous environment of the room (the Navier-Stokes equations in the Reynolds form), as well as for the components of the gaseous medium and the optical density of smoke, were solved. The research methods are presented in chapter 2, and the calculation results are presented in chapter 3.

Figure 1 describes the process of developing a methodology for increasing the fire resistance of cast-iron structures at cultural heritage sites.

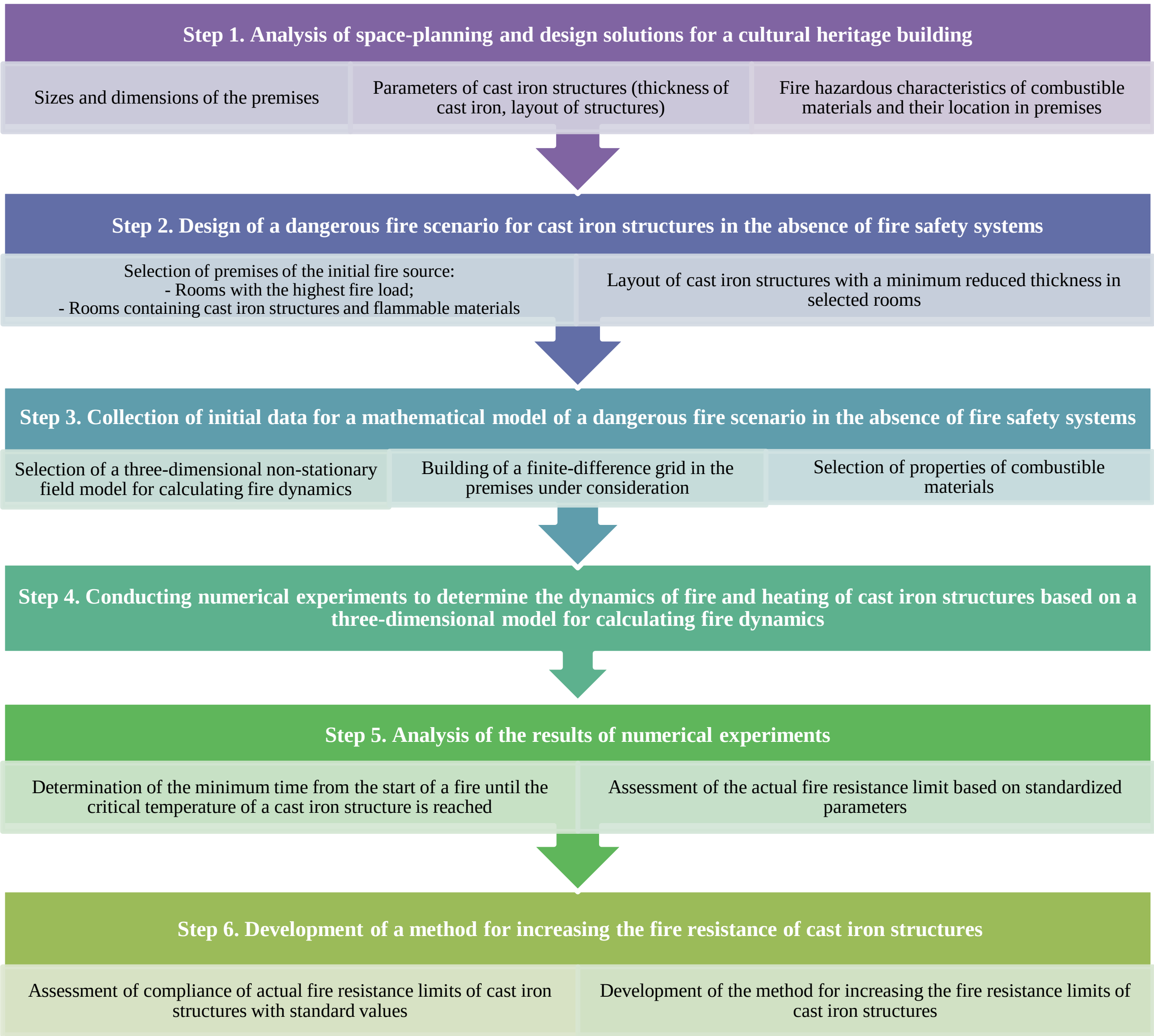


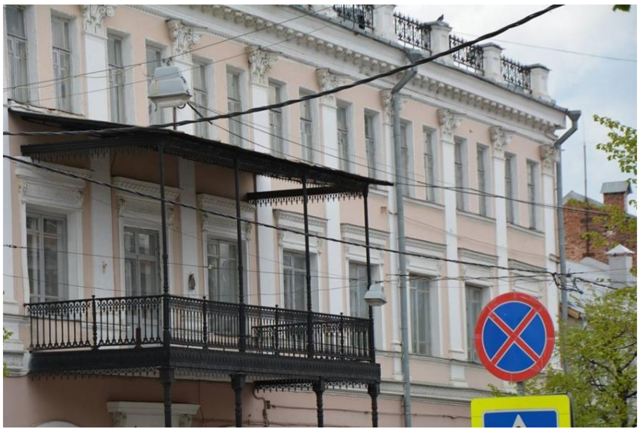
Figure 1. Flowchart describing the methodology for the increasing the fire resistance of cast-iron structures

2. Material and Methods

2.1. General Characteristics of The Research Object

The cultural heritage site under study represents the legendary historical building in the center of Yaroslavl, the Tsargrad Hotel. Construction began in 1790 and continued to be completed until the second half of the 19th century. The exterior of the building is shown in Figure 2.

(a)



(b)

Figure 2. Exterior view of the Tsargrad hotel building, Yaroslavl: a – photo of 1901; b – modern look

According to the layout inventories of the mid-1910s, on the ground floor of the building there were a bakery, a dairy shop, a hairdresser, and a colonial goods store; on the second and third floors there were living rooms. In the 1980s, the building was adapted for various institutions—a computing center, public utilities, publishing, printing management, etc. The building layout has been partially changed, and some decor in the interiors has been lost. The reconstruction project of the Tsargrad Hotel building was developed in 2019 in accordance with the assignment for the preservation of the cultural heritage site. The purpose of the reconstruction was to strengthen the loan-bearing capacity and increase the reliability of the main structural elements, provided that the original historical appearance was preserved.

The exterior of the building is shown in Figure 3. The floor plan (using the example of the second floor) is shown in Figure 2. Two internal staircases of type L1 (staircases with natural light through glazed or open openings in the exterior walls on each floor) are indicated in Figure 3 as staircase No. 1 and as staircase No. 2. Stairs lead from the corresponding entrances to the building, located on the ground floor, to the second, third, and fourth floors of the building. The supporting structures of stairs No. 1 and No. 2 are made of cast-iron profiles. The exterior of the building is shown in Figure 4.

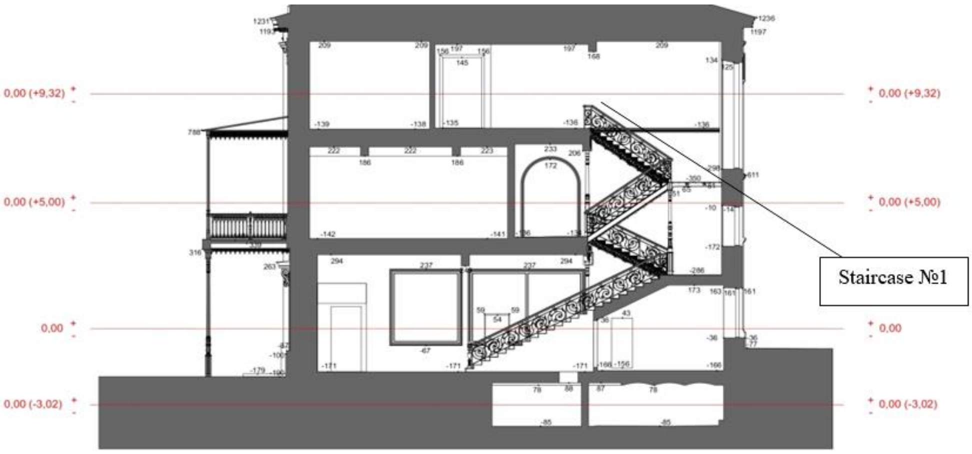


Figure 3. Section of the Tsargrad Hotel building (fragment)

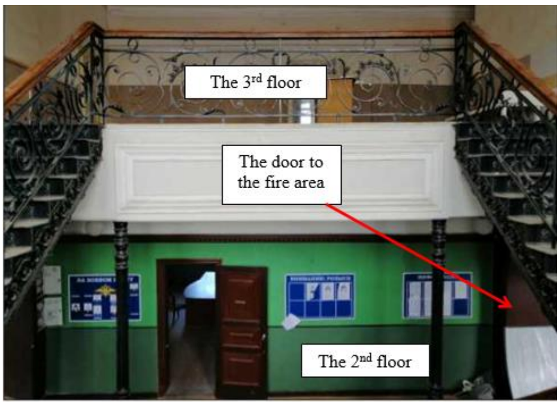


Figure 4. Cast-iron staircase exterior No. 1

It should be noted that in accordance with the established norms and requirements (Federal Law of the Russian Federation No. 123 "Technical Regulations on Fire Safety requirements"), all buildings and structures are classified into functional fire safety classes:

Class F1 — objects intended for living or temporary stay of people;

Class F2 — entertainment and cultural and educational facilities;

Class F3 — buildings of organizations serving people;

Class F4 — buildings of educational institutions, scientific and design institutes, institutions of management bodies;

Class F5 — industrial buildings and warehouses.

Taking into account the functional purpose of the building under study, the premises of the building belong to class F 1.2 (where F 1.2 is the symbol of the functional fire hazard class in accordance with current norms and requirements).

For building structures that differ in materials and purpose (load-bearing, enclosing, etc.), regulatory fire resistance limits are established. Building structures are classified according to the established fire resistance limits also into several classes and are presented in Table 1 by Dmitriev et al. (2019) [25]

Table 1. Fire resistance limit of building structures

Degree of buildings, structures, structures and fire compartments fire resistance	Load-bearing walls, columns and other load-bearing elements	External load-bearing walls	Interfloor ceilings (including attics and above basements)	Building structures of cordless coatings		Staircase building structures	
				Flooring (including with insulation)	Trusses, beams, runs	Interior walls	Marches and staircases
I	R 120	E 30	REI 60	RE 30	R 30	REI 120	R 60
II	R 90	E 15	REI 45	RE 15	R 15	REI 90	R 60
III	R 45	E 15	REI 45	RE 15	R 15	REI 60	R 45
IV	R 15	E 15	REI 45	RE 15	R 15	REI 45	R 15
V	not standardized						

2.2. Identification of the Fire Hazard Class of the Building and Establishment of Fire Resistance Limits for Load-Bearing Structures

The structural and functional parameter analysis of the building under study (Figures 2, 3, and 5) made it possible to determine the fire hazard class of the building and premises, as well as to establish fire resistance classes of load-bearing structures.

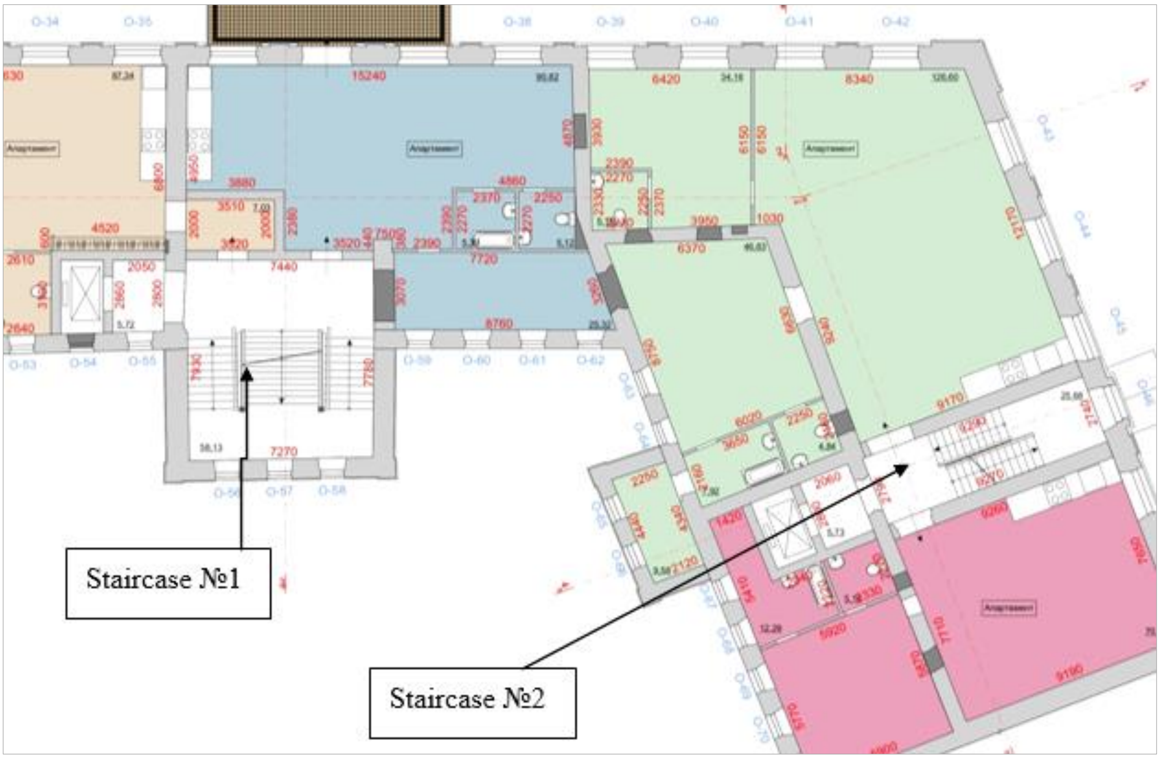


Figure 5. The second floor plan of the building (fragment)

The functional fire hazard class of the building is F 1.2 (hotels, dormitories, dormitories of sanatoriums and rest homes of general type, campgrounds, motels, and boarding houses). Built-in (internal) rooms belong to functional fire hazard classes F 4.3 and F 1.2:

- Fire hazard class of premises located on the ground floor of the building – F 4.3 (buildings of management bodies of institutions, design organizations, information and editorial publishing organizations, scientific organizations, banks, offices, offices);
- Fire hazard class of premises located on the second, third and fourth floors of the building – F 1.2 (hotels, dormitories, dormitories of sanatoriums and rest homes of general type, campgrounds, motels, and boarding houses).

Further, the limits of fire resistance of cast-iron structures are established. In accordance with fire resistance standards, the building has the III degree of fire resistance. Therefore (in accordance with the norms of the Federal Law of the Russian Federation No. 123 "Technical Regulations on fire safety requirements"), the required fire resistance limits of load-bearing cast-iron staircase structures are equal to R 45.

The staircases on the ground floor are separated from the rooms on the 1st floor by fire barriers with a fire resistance limit of REI 45. All doors on the second, third and fourth floors leading to the stairs are fire-resistant with a fire resistance limit of EI 45.

In the premises of the 2nd to 4th floors of the functional fire hazard class of the F1.2 building (hotels, dormitories, dormitories of sanatoriums and rest houses of general type, campsites, motels and boarding houses), the fire load density is assumed to be equal to the maximum of those listed in the technical regulations: 800 MJ/m^2. In the premises of the 1st floor of the functional fire hazard class of building F 4.3 (buildings of management bodies of institutions, design organizations, information and editorial publishing organizations, scientific organizations, banks, offices, offices), the fire load density is assumed to be equal to the maximum of those listed by Dmitriev et al. (2019) [25]: 1300 MJ/m^2.

2.3. Description of the Mathematical Model for Calculating the Fire Thermogasdynamics

A field fire model by Puzach et al. (2021) [26] is used to calculate heat and mass transfer. In this case, non-stationary three-dimensional differential equations of the laws of conservation of mass, momentum, and energy for the gaseous environment of the room (the Navier-Stokes equations in the Reynolds form) are solved. The above nonstationary three-dimensional differential equations are also used to calculate the components of the gaseous medium and the optical density of smoke [27]. All differential equations are reduced to the "standard" by Patankar (2018) [28], convenient for numerical solution:

$$\frac{\delta}{\delta\tau}(\rho F) + div(\rho\omega F) = div(G grad F) + S \tag{1}$$

where F is dependent variable; G is the diffusion coefficient for F; S is the source member; ρ – density, kg/m^3; w is speed, m/s; τ is time, s. In Equation 1 and further in numerical experiments, all values are time-averaged.

The effective viscosity of the gas μ_f in Equation 1 is represented as:

$$\mu_f = \mu + \mu_t \tag{1-1}$$

where μ, μ_t are, respectively, the coefficient of dynamic molecular and turbulent viscosity, kg/(s·m).

Effective thermal conductivity λ_f:

$$\lambda_f = \lambda + \lambda_t + \lambda_l \tag{1-2}$$

where λ, λ_t are, respectively, the coefficient of molecular and turbulent thermal conductivity, W/(m·K); λ_l is coefficient of radiant thermal conductivity, W/(m·K).

Effective diffusion of D_f:

$$D_f = D + D_t \tag{1-3}$$

where $D, D_t$are, respectively, the coefficient of molecular and turbulent diffusion, m^2/s.

The Smagorinsky model (Smagorinsky (1963) [29]) is used to calculate turbulent heat and mass transfer. The gas viscosity is determined by the Sutherland formula, the turbulent viscosity is determined by the Kolmogorov formula analysed by Puzach et al. (2022) [30]. The coefficient of turbulent thermal conductivity λ_t is determined from the ratio:

$$\lambda_t = c_p * \mu_t / Pr_t \tag{1-4}$$

where c_p is the specific mass heat capacity, J/(kg·K); Pr_t is the turbulent Prandtl number.

The turbulent diffusion coefficient D_t:

$$D_t = \mu_t / \rho * Pr_d \tag{1-5}$$

In calculations, we assume that Pr_t = Pr_d =1 by Mills (2018) [31].

The diffusion method (method of moments) is used to calculate radiant heat transfer [32]. The mass rate gasification of a solid fire load ψ is equal to work by Koshmarov & Svirshevskii (1972) [33]:

$$\psi = \psi_u \pi r^2 \tag{2}$$

where r is the radius of the combustion zone.

The radius of the combustion zone is determined by:

$$R = w_{pl}\tau \tag{2-1}$$

The rate of emission of the optical smoke density W during the burning of combustible material [33]:

$$W = W_u \psi \tag{3}$$

The combustion region is defined by volumetric sources of mass and heat evenly distributed in the volume of the combustion region.

The boundary conditions for Equation 1 are accepted:

a) On the inner surfaces of the enclosing structures, the velocity projections are zero; boundary conditions of the 3rd kind are given for the energy equation; for the remaining parameters, it is assumed that $\frac{\delta F}{\delta n} = 0$;

b) In an open opening in the area of gas out flow $\frac{\delta F}{\delta n} = 0$;

In the area of external air intake, the pressure, temperature and concentrations of the components correspond to the parameters of atmospheric air, where n is normal to the surface.

Equation 1 is solved by the control volume method by Patankar (2018) [28] according to an implicit finite-difference scheme on a checkerboard grid using a longitudinal-transverse sweep. In this case, an equation is used to correct (refine) the pressure in a compressible form. The distribution of the parameters of the gas medium inside each control volume is taken according to the scheme with differences against the flow. The accuracy of the calculations is controlled by the implementation of the local and integral laws of conservation of mass and energy in the computational domain.

The calculation of the enclosing structures heating is carried out based on three-dimensional differential equations of thermal conductivity, solved together with the system of Equations 1. A more detailed description of the mathematical model, as well as the results of comparing the calculation results according to the proposed model with the analytical solutions results, the integral model and experimental data is given by Puzach et al. (2021) [26]. The choice of parameters of the mathematical model is justified in the work of Puzach & Puzach (2005) [27]. In the above work, the correspondence of the developed three-dimensional thermodynamic model to the real process of fire development in rooms with complex geometry was established.

One of the main difficulties in solving a mathematical model on a computer is the choice of constraints and assumptions when describing a mathematical model. The accepted simplification of the geometry of the problem reduced the size of the finite difference grid to obtain a reasonable calculation time on a computer. Therefore, the presence of large-sized furniture, equipment, etc., was not considered in the room of the fire source, which led to a faster development of the fire and the release of combustion products and air into the stairwell. The accepted limitations of the parameters of the mathematical model do not reduce its adequacy to the real process of fire development.

2.4. Initial Data and Conditions for Conducting Numerical Experiments

The following initial data has been taken into account to select the fire mode:

- Small variable fire load at the site (no constant combustible load),
- High height of the structures.

Considering the above initial data, it is advisable to assess the fire resistance of structures in real fire conditions, and not in the "standard" fire mode by Kuz'mitskiy (2017) [34]. When conducting numerical experiments, a field method for calculating the fire dynamics hazards was used, justified by Puzach et al. (2021) [26] and software registered with the Federal Service of the Russian Federation for Intellectual Property, Patents and Trademarks [26, 34, 35].

The fire-technical characteristics of combustible materials in the premises of the building were determined by the standard fire load base [32] for buildings of the III degree of fire resistance, administrative premises and public buildings. The fire-technical characteristics of combustible materials are defined in Table 2.

Table 2. Fire-technical characteristics of combustible materials in the premises of the building

Characteristic	Designation	Unit	Room type		
			Building of the III degree of fire resistance	Administrative premises	Public buildings
			Combustible materials types of		
			Furniture + fabrics (0.75+0.25)	Furniture + paper (0.75+0.25)	Furniture + PVC floor covering (0.9+0.1)
Lower working heat of combustion	$Q\ n^{r}$	MJ/kg	14.700	14.002	14.000
Specific burnout rate	ψ_u	kg/(m^2·s)	0.0344	0.0210	0.0137
Oxygen consumption during combustion	L_{O2}	-	-1.437	-1.161	-1.369
Specific smoke emission	W_u	Np·m^2/kg	82.0	53.0	47.7
Flame propagation speed	w_{pl}	m/s	0.0465	0.0220	0.0150
Lower working heat of combustion	$Q\ n^{r}$	MJ/kg	14.700	14.002	14.000

It follows from Table 2 that the most dangerous for heating building structures is the fire load of a building of the III degree of fire resistance (furniture + fabrics), which has the highest values of the lowest working heat of combustion ($Q\ n^r$ = 14.700 MJ/kg) and the specific burnout rate (ψ_u = 0.0344 kg/(m^2·s)). Therefore, when calculating the most dangerous fire scenarios, we will use this fire load.

The thermophysical properties of cast-iron structures were determined by Buchanan et al. (2017) [36]: density ρ = 7270 kg/m^3; specific heat capacity c = 420 J/(kg·K); thermal conductivity coefficient λ = 52 W/(m·K). The critical temperature for cast-iron structures is assumed to be 636°C by Golikov et al. (2016) [23]. The indoor air parameters before the fire were taken as follows: temperature +20°C; pressure 1.013*10^5 Pa.

3. Results

3.1. The Most Dangerous Fire Scenarios Description

In all the most dangerous scenarios of fire development from the point of view of loss of bearing capacity by cast-iron load-bearing structures of stairs No. 1 and No. 2 connecting the corresponding entrances to the building on the 1st floor with rooms on the 2nd to 4th floors, it is assumed that the source of the fire is located on the 2nd floor in a room with access directly to the staircase the cage is through fire doors with a fire resistance limit of EI 45. All doors on the 2nd - 4th floors leading to the stairs are fire-resistant with a fire resistance limit of EI 45.

In the regulatory document (Order of the Ministry of Emergency Situations of Russia dated November 14, 2022 No. 1140 "On approval of the methodology for determining the calculated values of fire risk in buildings, structures and fire compartments of various classes of functional fire hazard"), it is established that if there is an additional fire–fighting measure (namely, the installation of fire doors on evacuation routes that open during evacuation), the probability of finding the fire door in the open position is 0.3. In this case, the fire door is assumed to be open to its full width and the spread of fire hazards to other floors of the building is allowed.

The most dangerous case is accepted in the work, in which the fire door leading from the room of the fire source to the staircase is open. The remaining fire doors of the 2nd-4th floors leading to the corridor in front of the staircase are closed. In such conditions, the fire continues until the combustible load of the room is completely burned out. The location of the fire source on the 3rd or 4th floors is less dangerous, since the height and intensity of combustion in the convective column, formed on the staircase from combustion products and air, will be greater compared to the location of the source of ignition on the 2nd floor.

The fire effect on the first floor on the actual fire resistance limits of cast-iron load-bearing structures of stairs No. 1 and No. 2 was not considered since the staircases on the first floor are separated from the premises of the first floor by fire barriers with a fire resistance limit REI 45. We accept the following assumption, which increases the reliability margin of the calculation results: we consider the one-dimensional equation of thermal conductivity, provided that heat transfer (cooling) from the zone of greatest heating along the cast-iron structure is neglected.

The minimum reduced thickness of the load-bearing cast-iron columns of the staircase No. 1 is 28.75 mm, the load-bearing cast-iron beams of the stairs No. 1 platforms have reduced thicknesses of 9.33, 9.459 and 31.20 mm; the reduced thickness of the stairwell slopes is 4.16 mm. The load-bearing cast-iron beams of the stairway platforms No. 2 have reduced thicknesses of 9,102 and 14.03 mm, the reduced thickness of the stairwell slopes is 5,612 mm.

The most dangerous fire scenarios leading to heating of cast-iron load-bearing structures of staircases No. 1 and No. 2 of the building are presented in Table 3 and Figure 6.

Table 3. Characteristics of the most dangerous fire scenarios leading to overheating cast-iron load-bearing structures of stairs No. 1 and No. 2

№ fire development scenarios	Staircase	The ignition source location	The minimum reduced thickness of the cast-iron structure, mm	Combustible load
01	№1	The apartment is located on the 2nd floor	4.16	Building of the III degree of fire resistance; (furniture + fabrics)
02	№2	The apartment is located on the 2nd floor	5.612	Building of the III degree of fire resistance; (furniture + fabrics)

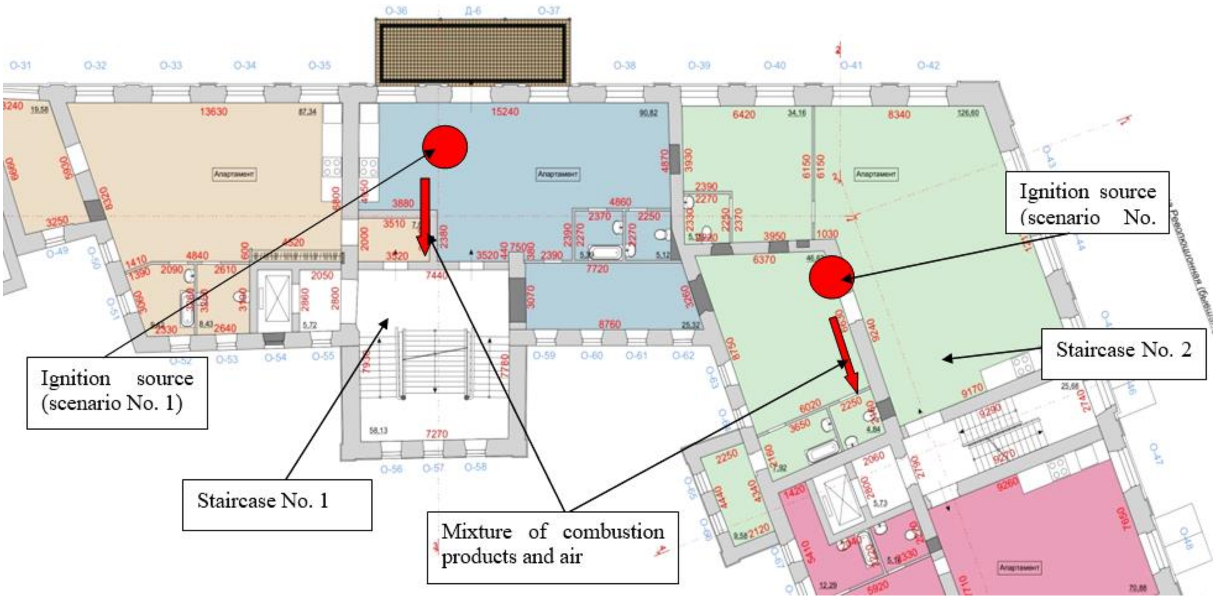


Figure 6. The most dangerous fire scenarios leading to heating of cast-iron load-bearing structures of stairs No. 1 and No. 2 on the 2nd floor of the building: a red circle is the fire source

The following dimensions of the premises of the fire centre were accepted:

- Scenario No. 01: the apartment is located on the 2nd floor (floor area is 90.82 m^2, height to the suspended ceiling is 3.3 m);
- Scenario No. 02: the apartment is located on the 2nd floor (the floor area is 126.6 m^2, the height to the suspended ceiling is 3.5 m).

With a maximum fire load density of q = 800 MJ/m^2 [25] in the premises of the fire source of functional fire hazard class F 1.2, the maximum heat release is equal to:

- Scenario No. 01: $Q= q\times F = 800\times 90.82 = 72{,}656$ MJ;
- Scenario No. 02: $Q= q\times F = 800\times 126.6 = 101{,}280$ MJ;

where F is the floor area of the fire source room, m^2.

To calculate the mass of combustible material, it is necessary to divide the maximum heat output by the lowest working heat of combustion of this type of fire load.

For the calculation, we select the fire scenario No. 01, since it is more dangerous than scenario No. 02 due to the smaller volume of the room (higher temperature of hot gases entering staircase No. 1) and a lower minimum reduced thickness of the cast-iron structure of staircase No. 1.

3.2. The Numerical Experiments Results and their Analysis

Calculations of the fire hazards dynamics (FH) and heating of load-bearing cast-iron structures of stairs No. 1 and No. 2 were performed using software [26, 35]. The dependences of the residual unburned mass of combustible material in the room of the fire source on the fire start time are shown in Figure 7.

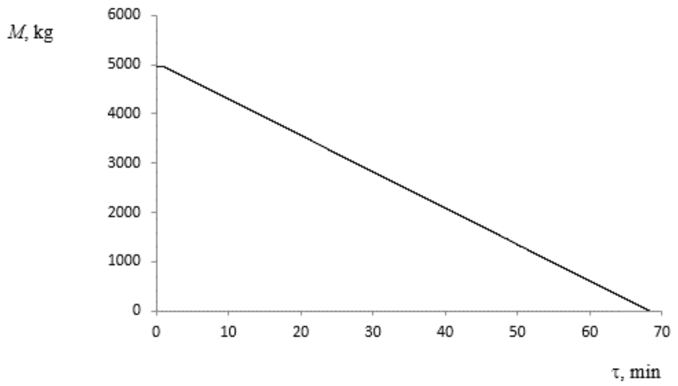


Figure 7. The dependence of the residual unburned mass of combustible material on the start time of the most dangerous fire scenario

Figure 7 shows that the maximum time of complete combustion of the fire load in the room of the fire in the most dangerous fire scenario does not exceed 68 minutes. Figure 7 shows the time dependences of the average volume temperature (Figure8-a) of the average volume partial oxygen density (Figure 8-b) and the mass flow rate of the gas mixture leaving the room of the fire through the open door to staircase No. 1, as well as the air entering the room through the open door from the staircase No. 1 (Figure 8-c).

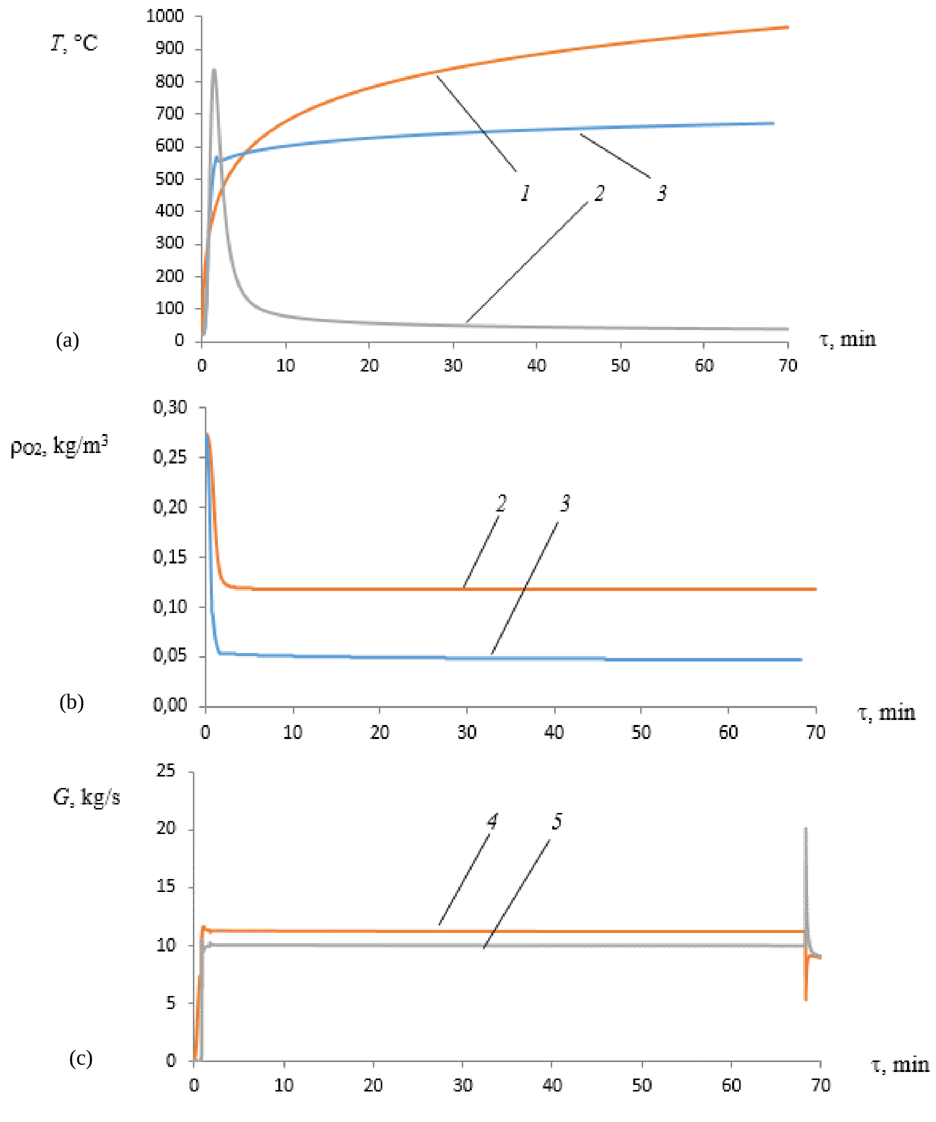


Figure 8. Depending on the fire time of the parameters of the gas environment of the fire source room: temperature (a), average volume partial oxygen density (b) and mass flow of gases and air through the open door of the fire source (c): 1 – the temperature of the "standard" fire; 2 – the fire door from the fire source room to the staircase No. 1 is closed;3 – the fire door from the room of the fire source to the nearest staircase No. 1 is open; 4 – the mass flow rate of the gas mixture leaving the room of the fire source through the open door to staircase No. 1; 5 – the mass flow rate of air entering the room through the open door from staircase No. 1.

The dependences on the fire time of temperatures in the most heated sections of load-bearing cast-iron building structures of staircase No. 1 with a minimum reduced thickness (the slopes of the staircase) are shown in Figure 9.

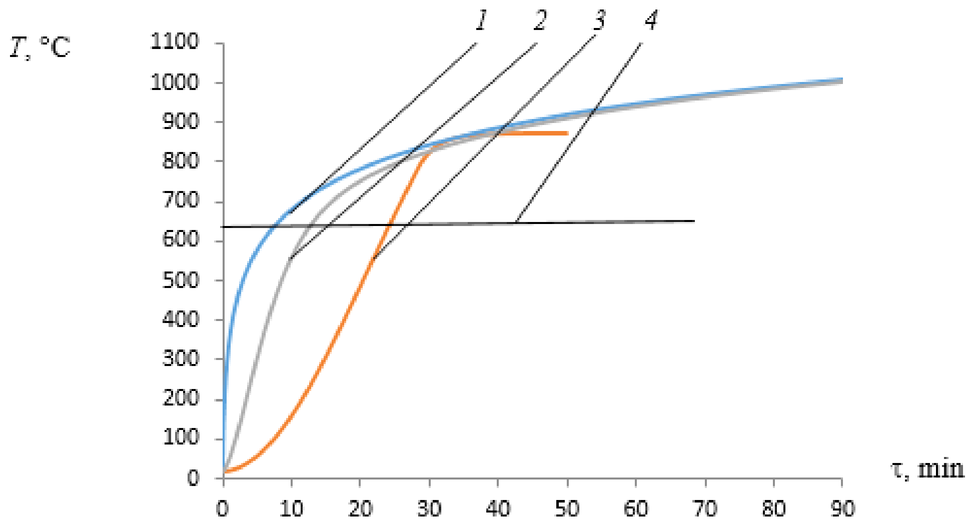


Figure 9. Temperature dependences on the fire time: 1 – the temperature of the "standard" fire; 2 –the maximum temperature of the supporting cast-iron structure of the staircase No. 1 with a minimum reduced thickness of 4.16 mm in a "standard" fire; 3 - the maximum temperature of the supporting structure of the cast-iron structure of the staircase No. 1 with a minimum reduced thickness located opposite the exit door of the room of the fire, in case of a real fire; 4 – the critical temperature of cast-iron T kr = 636°C.

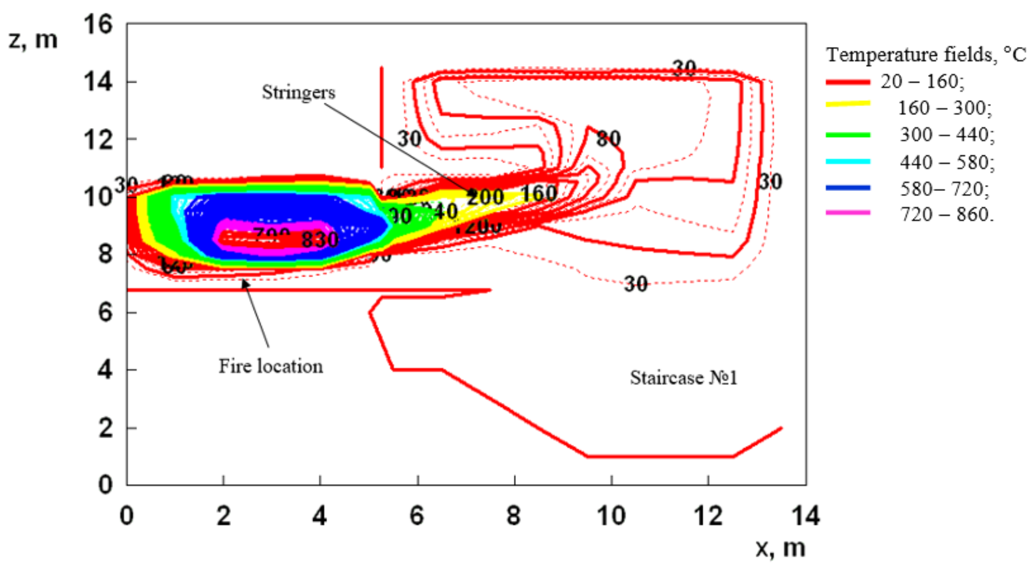
It can be seen from Figure 9 that the structure's maximum temperature with the minimum reduced thickness reaches a critical value for cast iron T kr = 636°C (Figure 9) at the following time intervals from the start of the fire:

- "Standard" fire: 11.2 minutes (line 2);

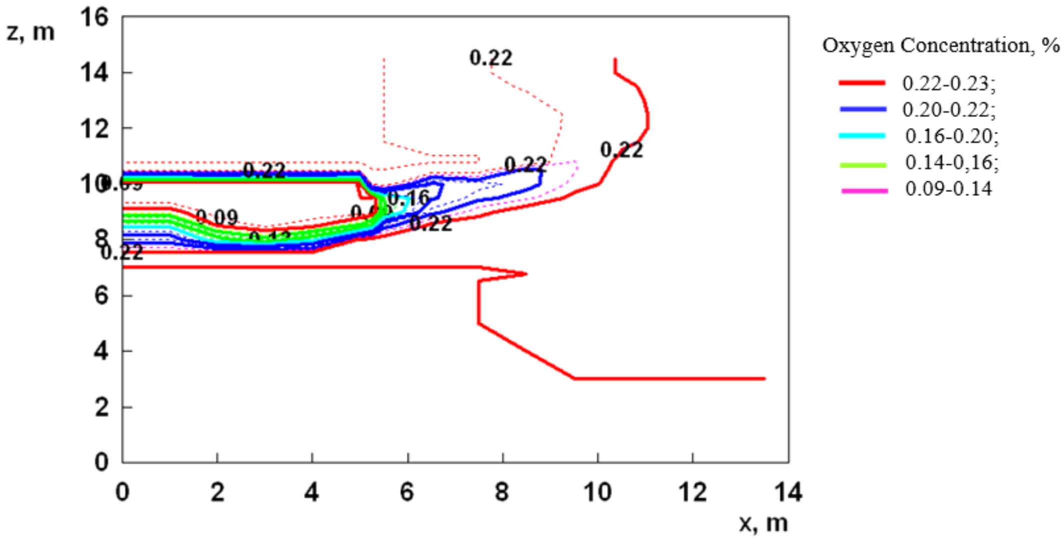
- Real fire: 20.6 minutes (curve 3).

4. Discussions

To illustrate and analyse the results of calculations of the dynamics of FH, Figures 10 and 11 show the temperature fields (in°C) and the mass concentration of oxygen and the flow patterns of the gas-air mixture in the cross sections of the premises of the fire source passing through the ignition source and the corresponding stairs at various intervals from the start of the fire with the fire door open, leading from the room of the fire source to the staircase.

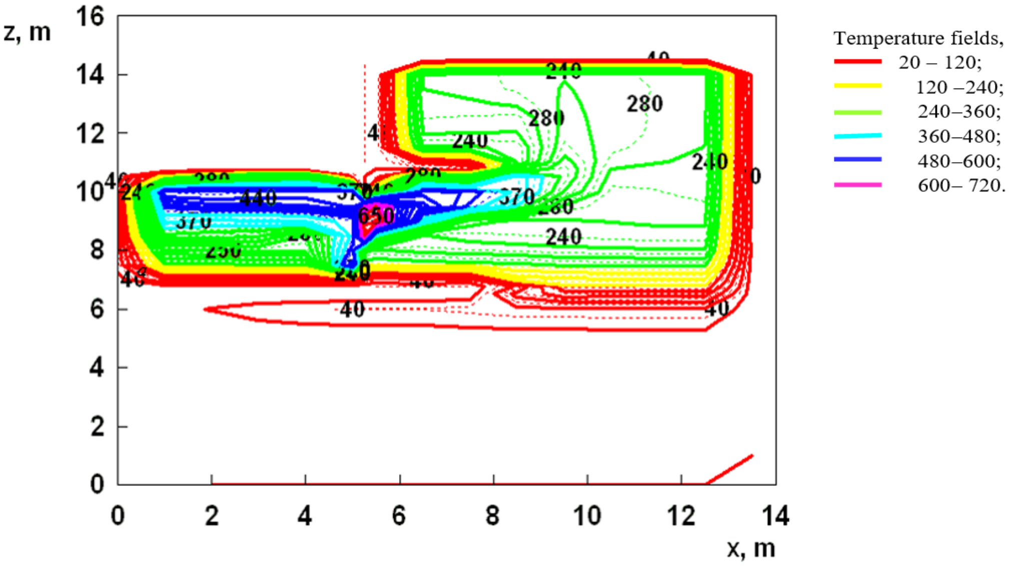


(a)

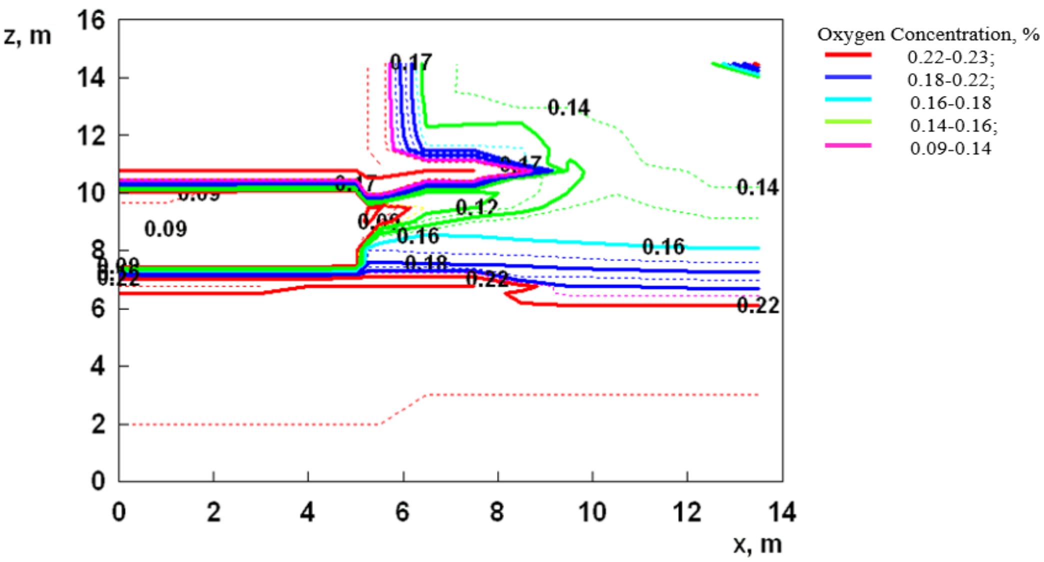


(b)

Figure 10. Temperature fields (a) and mass oxygen concentration (b) in the cross section of the room of the fire source passing through the ignition source and stairs No. 1 (1 min) after the start of the fire



(a)



(b)

Figure 11. Temperature fields (a) and mass oxygen concentration (b) in the cross section of the room of the fire source passing through the ignition source and stairs No. 1 (5 min) after the fire start

The analysis shows that in all considered dangerous scenarios of fire development, the temperature in a real fire is significantly lower than the temperature in the "standard" fire mode [23]. It can be seen from Figures 10 and 11 that the load-bearing cast-iron structures of stairs located opposite the exit door of the fire hearth are subjected to the most intense heating. This is due to the fact that unburned gasification products of combustible material leave the room of the fire source into the staircase and ignite in contact with the air entering through the door into this room.

Analysis of the results in Figure 11-a showed that the combustion zone is formed under the cast iron structure (with a minimum reduced thickness) at the doorway of the room. The width of this zone is approximately equal to the width of the open door. The height of the combustion zone along the z coordinate and along the x coordinate are approximately 2 m. The temperature of the gas mixture of combustion products and air in the rest of the staircase is significantly lower than the temperature at the doorway. For example, 5 minutes after the start of the fire, the gas mixture in the combustion zone has a temperature of approximately 700°C, and outside the combustion zone - approximately 280°C (Figure 11-a).

The calculations results of the dynamics of FH and heating of load-bearing cast-iron building structures of stairs showed by Golikov et al. (2016) [23] that the temperature of the load-bearing cast-iron structure of stairs No. 1 with a minimum reduced thickness (the slope of the landing) reaches a critical value T kr = 636°C at the following time intervals from the start of the fire: "standard" fire: 11.2 minutes; real fire: 20.6 minutes. Thus, the actual fire resistance limits of the staircase platform structure are less than the required fire resistance limit R45. Porter et al. (1998) [13] proposed to apply a fire-resistant layer of mineral wool to the surface of the structure to increase the fire resistance of cast iron. In our work, organizational and technical measures are proposed based on the calculation of a three-dimensional mathematical model. The difference lies in the fact that the authors of this work have developed measures to increase the fire resistance of cast iron structures that do not change the surface of cast iron and the geometric parameters of the structure.

The building is an object of cultural heritage, so the staircase surfaces cannot be treated with flame retardants. Therefore, it is necessary to develop fire-fighting measures that will not change the design of stairs.

With fire doors closed, the actual fire resistance limits of the stairs will correspond to the required fire resistance limits. According to the results of the conducted research, the most rational and effective method of increasing the fire resistance of cast-iron building structures is justified in the work: the development of a system for continuous monitoring of the condition of fire doors. To do this, it is proposed by Gu et al. (2021) [37] to use electromechanical reed sensors showing the opening of a fire door.

5. Conclusions

The analysis has shown that the known methods for calculating the actual fire resistance limits are based on the concept of a "standard" fire and do not consider the spatial planning solutions of the premises where the building structures are located. The behavior of cast-iron structures during their heating has been studied and compared to steel structures, even in conditions of a "standard" fire. The problem lies in the fact that existing methods do not allow calculating the actual fire resistance limits of cast-iron structures, considering the parameters of a "real" fire.

The study results have allowed to develop a new approach to ensuring that the actual fire resistance limits of cast-iron structures comply with the regulatory limits for the reconstruction of cultural heritage sites without changing the appearance of the object. The conducted analysis of the fire hazard of the facility has helped to describe the most dangerous scenarios of fire development, which can lead to heating and loss of bearing capacity of the cast-iron structures of the building. It has been found that when the fire doors are open, an outbreak of fire load gasification products occurs when interacting with the air inside the stairs.

The fire resistance limits of the cast-iron load-bearing elements of the staircase structure have been evaluated. It has been revealed that the actual fire resistance limit of a cast-iron element with a minimum reduced metal thickness is less than the normative value of the fire resistance limit. An effective method to increase the fire resistance of cast-iron building structures has been proposed. The research methodology is based on mathematical modeling of the most dangerous scenario for the development of a "*real*" fire, considering specific spatial planning solutions for the building, the type and location of combustible materials.

A comprehensive approach has been proposed to solve the conjugate problem of heat and mass transfer in the gas environment of a room in case of fire, thermal conductivity inside a cast-iron structure, and a strength problem (with setting the critical temperature for cast-iron). The method consists of a joint calculation under the most dangerous scenario of fire development of heat and mass transfer in the gas environment of the room, heating of the cast-iron construction of the staircase with the minimum reduced thickness (bevels), and subsequent comparison with the critical temperature for cast-iron. When the critical temperature of the cast-iron structure was reached, it was assumed that there was a loss of load-bearing capacity in the staircase. This ensures that the real thermogasodynamic conditions of the development of the most dangerous fire scenario are taken into account when calculating the actual fire resistance limits of cast-iron stairs.

Measures to increase the actual fire resistance limits of cast-iron stairs to the required limits during the reconstruction of cultural heritage sites without changing the appearance of cast-iron stairs have been developed. A system of continuous monitoring of the condition of fire doors has been proposed to ensure the required fire resistance limit of the building's cast-iron stairs.

In the future, it is necessary to continue the research on the development of a mathematical model for the joint solution of thermal and strength problems inside a cast-iron structure, adding new parameters to the research, such as the dependence of the strength properties of cast-iron on temperature and not on the critical temperature of cast-iron. This will expand the scope of the proposed methodology and contribute to improving the accuracy of calculating the fire resistance of cast-iron building structures.

6. Declarations

6.1. Author Contributions

Conceptualization, P.S.; methodology, P.S.; validation, L.L. and N.L.; formal analysis, P.S. and L.L.; resources, K.E.; data curation, D.E.; writing–original draft preparation, L.L. and T.V.; writing–review and editing, N.L. and K.L.; visualization, L.L.; supervision, P.S.; project administration, L.L. and K.E. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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