

The issue related to the conditions for creating the required temperature regime of fire when testing structures for fire resistance has not been studied in detail up to now. That necessitated determining the technical conditions under which it is possible to comply with the standard temperature regime of fire in the fire chamber of the furnace. The influence of the design parameters of the fire furnace chamber on the condition of compliance with the standard fire temperature regime when tested for fire resistance has been established. One of the most effective methods for examining such an impact is computer simulation. A computer model of the fire furnace was built on the basis of a comprehensive analysis and earlier work on the study of such furnaces, taking into consideration technical characteristics, in particular, geometrical parameters, fuel and air supply systems. The obtained research results are a prerequisite for scientific substantiation of the design parameters of fire furnaces and their engineering systems, which is necessary to comply with the standard temperature regime of fire in the furnace fire chamber. This makes it possible to provide the necessary conditions for testing building structures for fire resistance in compliance with the requirements of the relevant standards. The computer model constructed makes it possible to create the necessary temperature regime in the fire chamber of the furnace (in this study, the standard temperature of fire). As a result of the study, the technical parameters of the fuel supply and ventilation system were determined, which ensure compliance with the standard temperature regime in the fire chamber of the furnace. That makes it possible to build an automated complex of the testing process for fire resistance of building structures. In addition, the data obtained can be the basis for the design of such fire furnaces with the ability to comply with different fire temperature regimes without the intervention of the operator

Keywords: fire resistance, fire tests, fire furnace, thermal impact of fire, mathematical modeling

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INVESTIGATION OF THE INFLUENCE OF THE CONFIGURATION OF THE FIRE FURNACE CHAMBER ON THE TEMPERATURE REGIME DURING THE IMPLEMENTATION OF TESTS FOR FIRE RESISTANCE

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1. Introduction

Fire resistance estimation can be carried out by calculation and experimental methods [1, 2].

To determine the limits of fire resistance, the most common is the method of testing in special fire test furnaces. The basic principle assigned during such tests is to create test conditions in a special test furnace that are as close as possible to

the real conditions for the development of fire in the premises. To ensure the repeatability and reproducibility of the results of the values of the boundary of fire resistance of structures, the test conditions must be regulated. To this end, the range of permissible values for temperature deviations must be set for the values of the temperature curve of the standard fire mode and the necessary technical parameters of the process of fuel supply and the discharge of smoke gases from the fire chamber.

After all, deviations from the boundary of permissible values during tests can lead to distortion of results.

The issue of creating such conditions of heat and mass exchange in the fire chamber of the furnace, which ensure the uniform convective displacement of the gas environment of the fire chamber, is relevant. After all, this, in turn, affects the uniform distribution of temperature at each arbitrary point of the fire chamber. That determines maintaining the required temperature in the fire chamber of the furnace.

2. Literature review and problem statement

Paper [3] substantiated that existing software packages, in particular, for simulating thermal processes by means of computational gas-hydro-dynamics («CFD»), make it possible to take into consideration all the necessary parameters of the analyzed processes. Based on this, it was established that with the help of such systems, it is possible to study the influence of geometric and structural characteristics of the furnace for testing bearing walls on the adequacy of results. However, no universal procedure was considered that would determine the effect of geometric and structural characteristics of the furnace on the thermal processes occurring in the fire chamber. In addition, the cited study defined 2 main configurations of fire furnaces for fire resistance testing, which are common in special testing laboratories (Fig. 1).

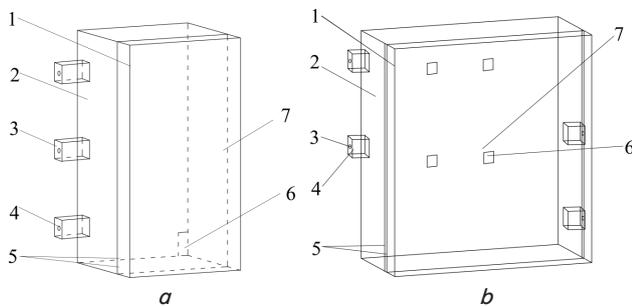


Fig. 1. Geometric configuration of vertical furnaces:
a – laboratory I (only symmetrical half is shown);
b – laboratory II: 1 – furnace fencing; 2 – fragment of the wall; 3 – blowing area; 4 – nozzle area; 5 – connected surfaces; 6 – combustion product discharge area; 7 – estimation area of the thermocouple

Based on computer simulations, article [4] reported a series of geometric configurations of vertical fire furnaces, in which the location and number of burners changed, as well as holes for the discharge of combustion products. The structural schemes of such installations are shown in Fig. 2.

At the same time, the issue of configuration and location of the flue gas discharge hole from the chamber of the fire furnace was ignored. The likely reason is a simplified approach to mathematical modeling of the process of mass-heat exchange in the study of temperature regimes. This, in turn, does not make it possible to apply the computer simulation to study the temperature regime in the furnace fire chamber, including the furnace IPA RCP.

Experimental studies of prototypes of enclosure structures for fire resistance based on loss of thermal insulation ability and integrity in the universal fire chamber for experimental research were carried out in [5]. The authors did not consider the question of the study of thermal processes using

computer gas hydrodynamics. That does not make it possible to extend the results to other structures of fire furnaces. In [6], the heat condition of building structures with a fire protection system was investigated during their testing in a special fire furnace under the influence of the standard temperature regime of fire. However, the conditions for creating the required temperature regime, as well as its observance within the specified limits, were not investigated. The algorithm of numerical analysis of transitional thermal processes in high-temperature gas chambers for ceramic firing has been developed in [7]. It is based on mathematical models of combined heat transfer, including combustion, turbulent burner flows and gas mixtures, heat transfer through radiation, conductivity, and convection. This makes it possible to assume that the existing software suites enable investigation of the features of burner combustion processes and in the furnace fire chamber, which directly affect compliance with the standard fire temperature regime. Work [8] proposes a method of simulation of fire with the setting of fire load, which makes it possible to investigate the behavior of building structures during a fire without conducting a full-fledged experiment. However, attention is not paid to the peculiarities of compliance with the temperature regime of the fire in which the effect on the structure occurs. In [9], thermophysical processes are considered, in particular, the measurement of heat flow, including in the combustion chamber. At the same time, attention is not paid to the peculiarities of fuel supply, and the design features of the combustion chamber. In work [10], the authors studied the features of measuring the density of heat flow in the combustion chamber. At the same time, attention is not paid to the study of the geometric characteristics of the source of such a stream, as well as the possibility of its configuration with the help of structural solutions and engineering equipment of the fire chamber. An option to overcome such difficulties is an integrated approach with the construction of an appropriate computer model. This approach is used in work [11] which examines the geometric model of the furnace fire chamber based on its drawings, the processes of gas combustion in it, using engineering modeling in ANSYS. As a result of solving such a model, scientifically-based results were obtained, which made it possible to consider computer simulation as an effective tool in the study of thermal processes. Features of computer algorithms for thermal control systems are presented in [12]. However, the cited work sets out the basic principles on which the construction of such models is based without specific application to fire chambers. That approach does not make it possible to investigate the impact of structural parameters and engineering systems to create the required temperature regime. The study of thermal processes with the help of software packages is reported in more detail in work [13]. In particular, the issue of creating heat flows, their movement, and their impact on structures is described. At the same time, again, the peculiarities of the source of thermal energy creation and its adjustment were not considered. A vivid example of building a numerical model of temperature distribution across load-bearing structures, subject to three fire scenarios, is presented in [14]. However, in the cited work, the issue of fire resistance of building structures is investigated, rather than features of creating the necessary temperature regimes. At the same time, the proposed method gives reason to believe that the solution of issues related to the creation of the necessary temperature regimes is possible using appropriate computer software.

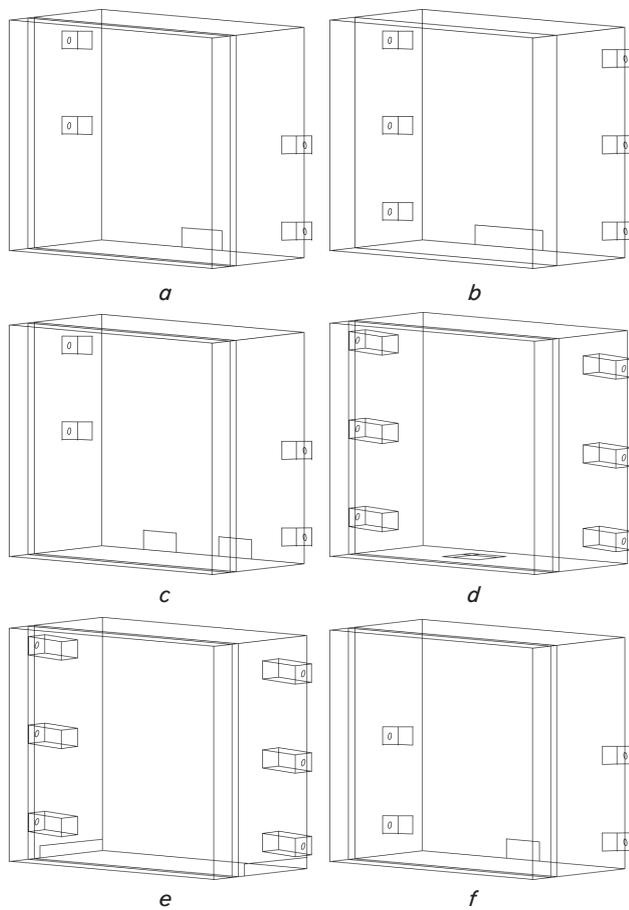


Fig. 2. Configuration of installations for tests on fire resistance of reinforced concrete walls: *a* – configuration A; *b* – configuration B; *c* – configuration C; *d* – configuration D; *e* – configuration E; *f* – configuration F

Based on our review, it was established that at present there are a number of works that address studying fire resistance, in particular, the features of heat-mass transfer, testing

of structures, the features of fastening building structures in the furnace fire chamber, changes in the structure of test samples, simulation of combustion processes occurring in a fire. However, the issue was ignored related to the conditions for creating the necessary temperature regime of fire when testing structures for fire resistance.

3. The aim and objectives of the study

The purpose of this work is to determine the influence of geometrical characteristics of the furnace chamber configuration and technical characteristics of fuel, ventilation systems, on compliance with the standard fire temperature regime.

To achieve this goal, it is necessary to solve the following task: based on the construction of a computer model, to determine the technical conditions under which it is possible to comply with the standard temperature regime of fire in the fire chamber of the furnace.

4. The study materials and methods

The research was conducted on the basis of the project documentation of a special fire furnace using computer software «FlowVision 2.5» (Russia). Before the beginning of mathematical modeling, we performed theoretical studies. As a result, the assumptions have been confirmed that the study into the peculiarities of creating temperature regimes in the furnace fire chamber is relevant. In particular, the impact of design parameters and engineering equipment on the possibility of observing the required temperature during the specified test time. When fitting parameters to the mathematical model, data from the reference literature were taken.

The technical characteristics of the special fire furnace IPA RCP, which were taken into consideration in the computer model, are given in Table 1.

The axonometric scheme of the fire furnace is shown in Fig. 3.

Table 1

Technical characteristics of the fire furnace

No.	Parameter	Indicator
1	Fire chamber working temperature range, °C	0 to 1,200
2	Fuel system electric drive power, V	380±10 %
3	Fuel flow rate for a fire furnace, kg/h	160
4	Pressure inside furnace, Pa	10±3
5	Heater type	Burner for liquid fuel
6	Number of burners	4
7	Burner ignition	Automated
8	Fuel pressure at furnace inlet, MPa	1.2
9	Air pressure at furnace inlet, kPa	6.0
10	Air consumption for burning, MAX, m ³ /h	2,000
11	Fire chamber dimensions:	
11.1	– depth, mm	1,980±10
11.2	– width, mm	3,240±10
11.3	– height, mm	3,100±10
12	Fire chamber volume, m ³	(19.88±0.100)
13	Vertical cut size, mm	400±10×500±10
14	Temperature regime inside furnace based on [2]	Standard
15.	Limit error of temperature measurement by a CHROMEL-ALUMEL type thermocouple, °C:	
15.1	At a temperature inside furnace to 375 °C	±1.5
15.2	At a temperature inside furnace from 375 to 850 °C	±3.0
15.3	At a temperature inside furnace from 850 to 1,100 °C	±4.0

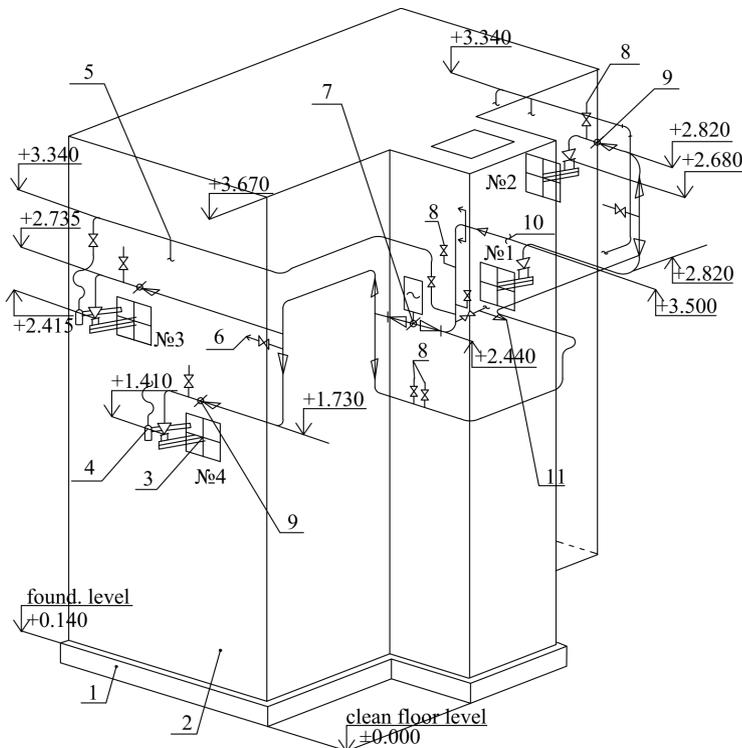


Fig. 3. Axonometric scheme of fire furnace: 1 – foundation; 2 – furnace body; 3 – burner; 4 – ignition burner ZMI-25; 5 – air supply to the ignition burner and low-frequency photosensor; 6 – air for blowing the burner; 7 – throttle blocker DKL-200 with electric drive; 8 – power supply controller (KIP-1); 9 – vane DKL-80; 10 – air supply from the electric fan; 11 – air to cool the inspection window

During the operation of the furnace, fuel is supplied from the tank to the burners. The temperature in the fire chamber is regulated by the volume of a combustible air-fuel mixture using a valve. Combustion products are removed through the smoke tube and chimney. The leakage of combustion products is regulated by a gas pipeline flap. Diesel fuel is used to heat the furnace. The furnace is made of a metal case, located on a concrete foundation, which has a channel for the discharge of combustion products. The fire chamber inside is lined with bricks, lined with slabs made of material made on the basis of silica fiber (PTCV-220) and one row of refractory bricks. The thickness of the lining made of PTCV-220 is 60 mm. The thermal inertia of lining at a temperature of 500 °C is $230 \text{ W s}^{0.5} \text{ m}^{-2} \text{ K}^{-1}$. The general view of the fire chamber in a special fire furnace is shown in Fig. 4.

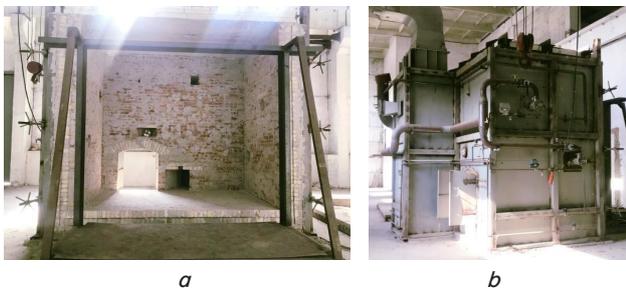


Fig. 4. Fire furnace IPA RCP: a – fire chamber; b – general view

Measurement and registration of temperature in the furnace are carried out by the measuring-information sys-

tem «Thermocont» with a measuring module of type «ADAM-508» and not less than five thermocouples of CHROMEL-ALUMEL type. Wire diameter – 1.2 mm. The thermocouple protective casing has been removed (cut off and removed) at a length of 35 ± 5 mm from the thermocouple measuring joint. Temperature measurement and registration should be carried out at intervals of 60 s. A feature of the location of thermocouples in the furnace is that they are arranged in a checkerboard pattern.

The arrangement of fuel supply systems and chimney fire control of the furnace was carried out based on the method of expert estimates.

5. The results of studying the impact of the design parameters of the furnace chamber on the conditions of compliance with the standard fire temperature regime

In order to check the possibility of compliance with the standard temperature regime in the fire chamber of the special fire furnace IPA RCP during experimental studies, it became necessary to model the combustion of diesel fuel in the furnace chamber. At the initial stage of computer simulation, a CAD model of the furnace was built, whose parameters were set according to Table 1 (Fig. 5).

The next step was to build a grid model of the furnace.

The method of control volumes, which is used in the software suite, has certain features.

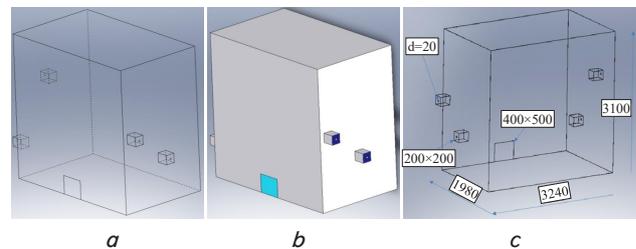


Fig. 5. CAD-model of the special fire furnace IPA RCP: a – the general view of the geometry of the fire chamber; b – geometric zones of boundary conditions; c – geometric dimensions of zones of boundary conditions

Numerical integration of equations by spatial coordinates is carried out using a rectangular, adaptive, locally split grid. This approach makes it possible to use a simple uniform non-adaptive grid when performing tasks with relatively simple geometry.

There is a directly proportional relationship between the accuracy of the calculation and the number of estimation cells, and inversely proportional – between the number of cells and the time over which the calculation is performed. Therefore, it is necessary to choose the balance between the required calculation accuracy and the time to be spent on the calculation.

The grid model of the fire furnace space is shown in Fig. 6. Parameters for calculating heat transfer in the fire furnace in the system «FlowVision 2.5» are given in Table 2.

- The following initial conditions were set:
- temperature – 23 °C;
 - pressure – 101,300 Pa;

- fuel – diesel fuel – two-phase combustion (liquid+gaseous);
- air inflow – forced (air).

The initial parameters of the boundary conditions of the fire furnace are given in Table 3.

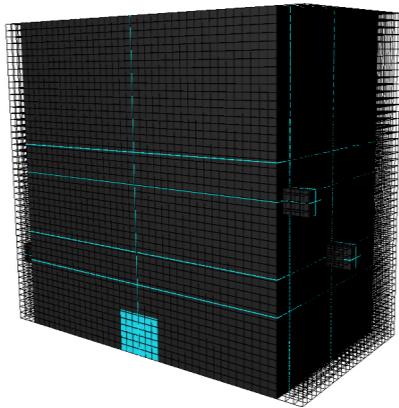


Fig. 6. Grid model of furnace space

After setting the initial parameters of the boundary conditions of the fire furnace and building the appropriate model, the calculation process was started. The results are shown in Fig. 7. In addition, the process of mixing fuel and air in burners is visually presented, as well as the flame torch (Fig. 8).

Temperature control inside the furnace fire chamber was carried out at five points at a distance of 100 mm from the front wall. Checkpoints are shown in Fig. 9.

Thus, subject to the required combination of fuel and air supply to the burners of the furnace fire chamber, the standard fire mode is fully observed in it. To this end, it is necessary:

- to ensure the supply of diesel fuel particles of at least 0.13 kg/s per nozzle. The number of nozzles is 4. At the same time, the total fuel consumption should be 18 l/h. That is, the required fuel reserve for all 4 nozzles should be approximately 36 liters for a 2-hour test, which will ensure compliance with the standard fire temperature regime;
- to ensure air supply simultaneously with fuel with a normal mass speed of 3.5 (kg/m²·s). The area of the holes is 0.04 m² each. Thus, it is necessary to ensure an air inflow of 0.1 kg/s from each device for injection.

Table 2

Parameters for calculating heat transfer in a fire furnace

No.	Math model parameter	Feature	Parameter specification
1	Computation grid	Must be small enough, while ensuring the required calculation performance	Number of computational cells: 46,200. Total number of cells: 58,404. Cell volume: 3.4·10 ⁻⁴ m ³ . Dimensions (approximately): 0.07 m side
2	Calculation scheme	Computational algorithm scheme	Implicit scheme
3	Global time increment	Set to ensure the correctness of the calculation	Assigned by introducing the constant associated with the Courant-Friedrichs-Levi CFL=1 criterion in the initial stages of the initiation of combustion CFL=25, for the steady combustion process

Table 3

Initial parameters of the boundary conditions of the fire furnace

No.	Sub-area	Boundary condition type in line with the range of «FlowVision 2.5», m ²	Parameter	Value/measurement unit
1	Furnace fencing	Wall	Irradiation energy density	Radiation flow considered
2	Inflow area	Inlet/outlet	Temperature	25 °C
			Flow rate	3.5 kg/m ² s
			Turb energy	0.03
			Turb dissipation	0.001
			O ₂ Restored	0.2333
3	Valve area	Wall	Boundary condition type	freq+norm speed
			Particle flow	0.013 kg/s
			Particle temperature	25 °C
			Particle diameter	0.0001 m
			Mass share	1
			Particle blackness	0.5
			No. start. points	100
Particle speed	10 m/s			
4	Smoke hole area	Free release	By default	-

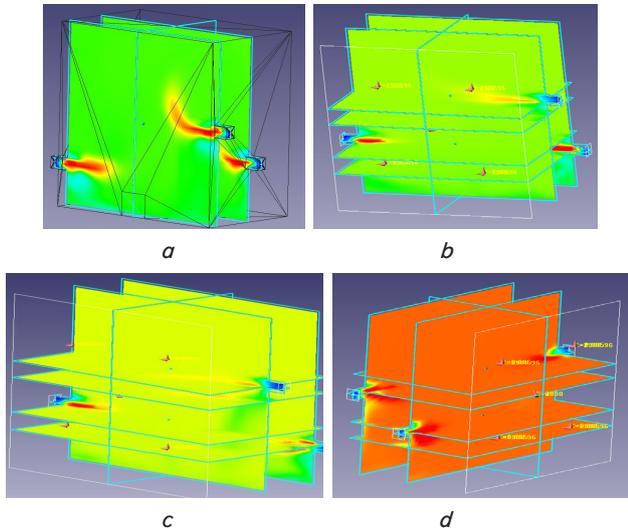


Fig. 7. Temperature regime of the fire chamber of a special fire furnace: *a* – minute 1 of fire action; *b* – minute 5 of fire action; *c* – minute 10 of fire action; *d* – minute 30 of fire action

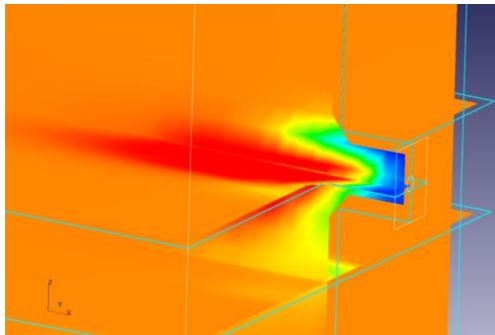


Fig. 8. Mixing fuel and air in burners, visualizing a flame torch

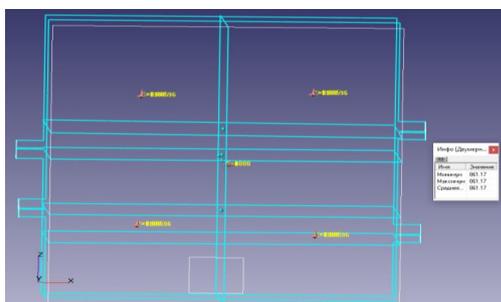


Fig. 9. Places of temperature measurement in the fire chamber of a special fire furnace

During the computational experiment of this study, temperature control was organized so that the average temperature in the chamber of the simulated furnace coincided with the curve of the standard fire temperature regime as much as possible and did not go beyond the permissible limits of the test [2]. To this end, by means of control of the «FlowVision 2.5» system, the current data from the thermocouple were recorded interactively. In the case of reaching the maximum temperature for a certain step in time, the parameters of the combustion process changed.

The results of temperature change in the fire chamber of a special fire furnace are shown in the form of a plot (Fig. 10).

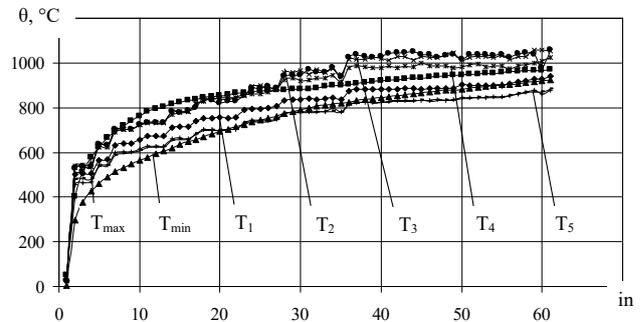


Fig. 10. Temperature change plot in different places of the vertical furnace chamber: T_{max} – the upper limit of tests; T_{min} – the lower limit of tests; T1–T5 – temperature indicators in the furnace chamber

The plot in Fig. 10 demonstrates that all five temperature control points in the furnace’s fire chamber recorded temperatures that did not go beyond the lower and upper limits of the tests. This ensures that the parameters of fuel and air supply for this configuration of the fire chamber calculated during the solution of the mathematical computer model ensure compliance with the standard temperature regime.

6. Discussion of results of studying the conditions of compliance with the standard fire temperature

The results obtained during the research ensure the standard temperature of the fire during the entire test period. This is missed in work [14] since attention is paid to the distribution of temperature across construction structures, while the conditions under which the necessary temperature regimes are created were not fully taken into consideration. The result of our study is confirmed by the plot of temperature changes in different places of the fire chamber of the vertical furnace, shown in Fig. 10, as well as by visualizing the temperature distribution in the furnace fire chamber at different intervals of the test time, which is shown in Fig. 7.

It should be noted that compliance with the standard temperature in the fire chamber of the furnace is possible only if the supply of fuel with air in the required amount to the heating channels is ensured. Given this, the process of mixing fuel and air in burners with the visualization of the flame torch is illustrated in Fig. 8. The specified parameters were defined during the computational experiment using the constructed computer model of the process of mass-heat transfer in the chamber of the fire furnace. The peculiarity of the computer model built is that it simultaneously takes into consideration the geometric characteristics of the furnace chamber configuration, the technical characteristics of the fuel, ventilation system, unlike [4], where the result does not take into consideration the peculiarities of fuel and air supply to the burners. This becomes possible by fitting the corresponding parameters to the initial boundary conditions of the computer model. Combined, this makes it possible to adjust the required fuel and air supply to comply with the required temperature regime, depending on the volume of the fire chamber, the characteristics of the location of the burners. Owing to the computer model, the temperature regime of the fire chamber of a real furnace was reproduced. That makes it possible during tests of building structures for fire resistance using software suites in the initial boundary conditions of

the model to set the standard temperature regime of the fire, which would be within those boundaries that are as close as possible to the real experiment.

The computer model built in this work is tested using the furnace IPA RCP. To study the characteristics of fuel supply, air, fire chamber configuration of other fire furnaces, it is necessary to change the initial data fit to the model. Thus, the results obtained in this work cannot be universal for fire chambers of existing furnaces. This is due to the fact that each individual type of furnace has its specifications. However, the principle underlying the construction of boundary conditions of the computer model makes it possible to obtain the necessary parameters of fuel and air supply to the burners, depending on the geometrical parameters of the fire chamber of the furnace under investigation. That makes it possible to provide the required temperature mode during the entire test period. That is, this result is practically important both at the design stage and at the stage of operation of the test furnace.

The current study has significant prospects for advancement since it is very important from a practical point of view in order to obtain reliable results during fire resistance tests. This work may be advanced by compiling engineering tables on the required fuel and air supply, depending on the design parameters of the furnace based on the computer model built. Such tables can be calculated for the main types of fire furnaces, taking into consideration their configurations.

Thus, by applying the underlying principles of the computer model, it is possible to conduct research into the main

types of configuration of fire furnaces and to standardize values to be obtained.

7. Conclusions

Based on the construction of a computer model, technical conditions are determined under which it is possible to comply with the standard temperature regime of fire in the fire chamber of the furnace. The basic elements of which are the parameters of fuel and air supply to the burners. These parameters were obtained while solving the computer model based on the software suite «FlowVision 2.5». Their reliability was achieved by fitting data on the initial boundary conditions from the reference literature and numerical integration of equations by spatial coordinates using an adaptive grid when building a furnace fire chamber. In addition, when solving a computer model, in addition to the fuel supply system and ventilation of the furnace, the geometric configuration of its fire chamber was taken into consideration. Such an integrated approach, demonstrated to achieve the goal of the current study, is lacking in known works of the scientific community. Most scientific papers do not pay attention to the peculiarities of fuel and air supply when building computer models to obtain the necessary temperature in fire chambers. Additionally, in this study, we took into consideration the design features of burners with the representation of the visualization of the torch of their flame. The required fuel supply for all burners for testing within 2 hours has been determined.

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