Increasing the Efficiency and Environmental Friendliness of Fire Resistance Assessment Tools for Load-Bearing Reinforced Concrete Building Structures

Oleksandr Nuianzin[1*], Serhii Pozdieiev[1], Stanislav Sidnei[1], Tetiana Kostenko[1], Anna Borysova[2], Taras Samchenko[2]

[1] National University of Civil Defence of Ukraine, 94 Chernyshevska Str., Kharkiv, 61023, Ukraine

[2] Institute of Public Administration and Research in Civil Protection, 21 Vyshhorodska Str., Kyiv, 04074, Ukraine

* Corresponding author's email: nuianzin_oleksandr@chipb.org.in

ABSTRACT

In this work, it is substantiated that it is possible to create a fire installation with parameters that will ensure higher environmental friendliness of the tests compared to large-sized furnaces. At the same time, its configuration will be universal, compact and capable of high reproducibility of experimental results. A full factorial experiment was conducted. According to its results, the parameters of the furnace chamber, which most significantly affect the reproducibility of the results, were determined. This are the volume of the chamber, the distance from the burners to the surface of the examined fragment of the load-bearing reinforced concrete building structure, and the height at which the opening for the exit of combustion products is located. Adequacy of operation of the designed installation was verified by the computer simulation method. Natural gas was used as fuel. On the basis of the received data, a sketch of the installation was created for conducting the experimental part of evaluating the fire resistance of load-bearing reinforced concrete building structures under the influence of the standard fire temperature regime. It can ensure a high degree of reproducibility of the test results.

Keywords: fire furnace, test, experimental method, fire resistance, reinforced concrete, efficiency, environmental friendliness.

INTRODUCTION

Over the past 5 years, the number of fires has increased, particularly in industrial and residential buildings. It is important to ensure fire resistance of both individual elements of building structures and their structures as a whole. There are experimental and calculation methods for evaluating fire resistance. However, these methods have drawbacks. Calculation methods do not take into account the features of the materials included in multi-composite solutions, and experimental methods are non-ecological and time-consuming.

During fire resistance tests, large-sized fire installations are used. For their heating, liquid fuel is used: heavy oil, diesel and kerosene, which can harm the environment. In addition, it is not always possible to take into account the real dimensions of the building structure and the load acting on it during the tests.

Standard fire resistance tests have been used in the design of building elements for more than a century. Initially, norms were developed to provide comparative indicators of the level of fire safety of non-combustible products and elements. There are important questions about the suitability of standard fire resistance tests for combustible structural elements (Bartlett et al., 2020). There are European standards (EN 1363-1:1999, 1999 and ISO 834-1:1999, 1999) for evaluating the fire resistance limit of building structures, which describe the method of fire resistance tests using special installations. The essence is to determine the time interval from the beginning of the test to

the onset of one of the limit states of fire resistance standardized for this design under the conditions of the standard fire temperature regime (ISO/IEC 17025:2005, 2005).

Large-sized furnaces in which it is possible to evaluate the fire resistance of building structures of standard size are mainly used in Ukraine and in the world, (Pozdieiev et al., 2020). However, these furnaces have a significant drawback in terms of efficiency: their tests are time-consuming and non-ecological (Nuianzin et al., 2021).

As an alternative fuel, researchers have proposed the use of gas as a more environmentally friendly substance. The rate of fuel consumption in the furnace during standard tests was determined. Energy released during combustion was also determined. External fuel supply (from natural gas supplied to the furnace) was approximately 3 MW. This value was recorded during the concrete test (Bartlett et al., 2020).

The validity of the results of the mathematical modeling of the tests has also been questioned due to limitations and contradictions. The researchers analyzed 153 fire resistance tests (117 flexural members, 6 compression members, and 30 tension members) for The Reduced Cross-Section Method (RCSM). The analysis showed that most of the results are of low quality or are incomplete. For building elements under load, the results agreed well with RCSM, but significant deviations were found for elements in compression and bending. Therefore, it was recommended to revise the existing design approaches. This will include the results of preliminary calculations and relevant tests (Schmid et al., 2014).

Scientists have conducted separate studies on metrology tools. In particular, the application of plate thermometers is described, as well as the basic theoretical analysis of heat exchange conditions in furnaces. The fire resistance of the building structure tested in different furnaces was evaluated, respectively. Results differed by 25% in individual cases. Heat transfer to the test sample in the test furnace at high temperature depends primarily on the radiant flux, not on convection. Thus, the heating chambers must have sufficient volume so that radiant heat transfer dominates, and at the same time they must have a fast thermal response (Wickström, 1994). In this case, there is no difference in terms of the accuracy of the results, regarding the type of fuel that is used. And from the point of view of ecology and efficiency, it is more appropriate to use gas.

Therefore, the improvement of methods and means of assessing the fire resistance limit of load-bearing reinforced concrete building structures, which will contribute to increasing environmental friendliness and have high efficiency, is an urgent task.

THE PURPOSE AND OBJECTIVES OF THE STUDY

One of the institutes in Ukraine created a compact furnace and investigated the process of heating a wall structure. However, the design of the furnace involves the use of only one burner for heating the chamber. This affects the uniformity of heating of building structures. Thus, it is impossible to ensure the reproducibility of the results. In addition, this furnace can only be used for wall testing and runs on liquid diesel fuel. This, in turn, indicates the imperfection of the configuration in terms of ecology (Demchyna et al., 2014).

Summarizing the above, this work is devoted to research aimed at the development of a new fire installation. The main requirements for its configuration are environmental friendliness, versatility, compactness and high reproducibility of experimental results.

The purpose of the study is to substantiate the parameters of the furnace chamber and the placement of its key elements, which will have universality, compactness, high reproducibility of results and will ensure higher environmental friendliness in comparison with large-sized installations.

To achieve this objective, the following tasks have been solved:

- to propose the concept of a universal furnace chamber, which will make it possible to heat the main types of fragments of load-bearing reinforced concrete building structures;
- to perform calculations and determine the parameters that most significantly affect the reproducibility of the results;
- to establish patterns of dependence of temperature dispersion in the chamber of the fire furnace on the determined parameters;
- to create a computer model of the furnace chamber based on the received data and investigate its efficiency;
- to propose a sketch of the installation based on the conducted research.

The subject of the study is the parameters and configuration of a universal small-sized fire installation.

The object of the study is heat and mass transfer during heating of load-bearing building structures in fire furnaces. The study methods – the study was carried out on the basis of systems of differential equations of continuous media such as the Navier-Stokes equations and heat conduction equations under heating conditions.

STUDY RESULTS

To date, large-sized furnaces are used in the world for experimental evaluation of fire resistance of reinforced concrete building structures. But they are not able to meet the load requirements or test structures of real sizes. Therefore, there is no need to create huge installations. The possibility of creating a universal small-sized fire installation, which is able to provide conditions for uniform heating of structures, and then carry out calculations based on the received data was determined.

At the first stage of the work, an algorithm was developed to create a computer model of a fire furnace with flare combustion. A total of 10 configurations were created that differed in the geometric parameters of the chamber (width, depth, height), the number of burners (from 2 to 4), the number and location of holes for the removal of combustion products (from 1 to 2).

Computer simulation using CFD was carried out. A mathematical apparatus for developing models of a fire furnace for testing fragments of reinforced concrete building structures, based on the use of a complete system of Navier-Stokes equations and gas fuel, the combustion of which can be calculated according to the Zeldovich or Magnusen models.

On Figure 1 the general concept of geometric configurations of fire furnaces created in the FDS software complex is presented.

The performed calculations and the obtained results of computer modeling allow us to take as a basis the hypothesis that the dispersion of temperatures on the heating surface of fragments of reinforced concrete structures has a linear dependence on the most significant parameters. The most significant parameters in this case are the volume of the camera V (m^3), distance to burners l (m), as well as the height of the opening for the removal of combustion products h (m). Taking into account the accepted hypothesis of linear dependence, its mathematical model can be built on the basis of regression:

$$S^2 = p_0 + p_1 x_1 + p_2 x_2 + p_3 x_3 + p_4 x_1 x_2 + p_5 x_1 x_3 + p_6 x_2 x_3 + p_7 x_1 x_2 x_3 \quad (1)$$

where: p_0, p_1, p_2, p_3, p_4, p_5, p_6, p_7 – regression coefficients.
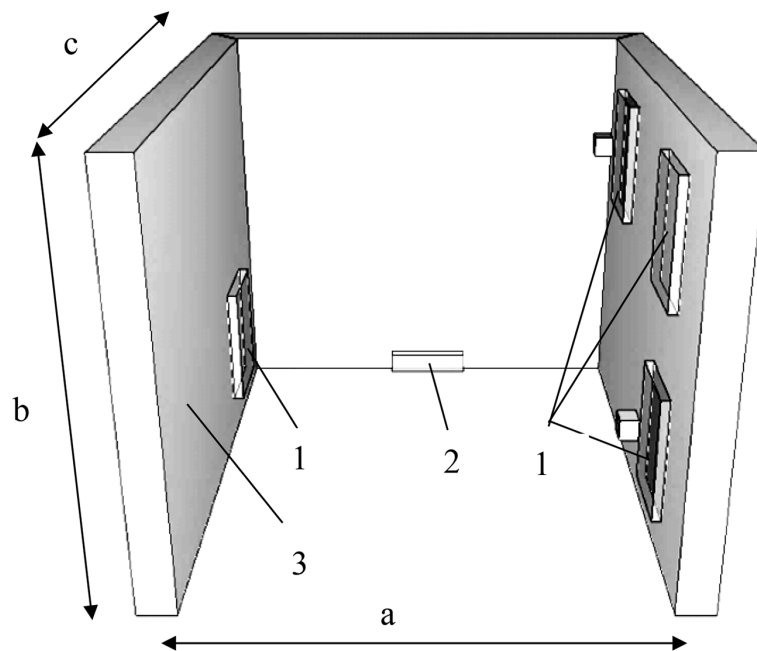
Figure 1. General view of configurations of fire furnaces, 1 – burners and air inlets, 2 – the location of the opening(s) for the exit of combustion products, 3 – U-shaped enclosure of the furnace chamber

The regression coefficients (1) are calculated on the basis of 8 numerical experiments. Numerical experiments are carried out on a simple orthogonal plan corresponding to the plan matrix given below in the form of Table 1.

In Table 1, the accepted limits of the ranges in which the specified factors change when conducting a numerical full factorial experiment to build a mathematical model of the dependence of the temperature dispersion on the above parameters are given.

Based on the ranges of variation of the factors presented in Table 2, using the matrix of the fully factorial experiment plan according to the Table 1, the necessary calculations were performed and the values of temperature dispersion along the heating surface of the examined fragments of reinforced concrete building structures were obtained. The results of the calculations are given in the Table 3.

Below there are the results of a full factorial experiment to determine the temperature dispersion on the heating surface of fragments of load-bearing reinforced concrete structures.

Based on the numerical values of the Tables 1 and 2, regression coefficients (1) were calculated. The results of calculations for determining the regression coefficients are presented below in the Table 4.

After processing the data, a regularity of the dependence of fire resistance on the most significant parameters was established: the volume of its chamber (V), the distance from the burners to the surface of the investigated fragment of the load-bearing reinforced concrete building structure (l) and the height at which the opening for the exit of combustion products (h) is located in the form:

$$S^2 = 4221 + 4133 \cdot h - 2555 \cdot l - 1220 \cdot V - 800 \cdot V \cdot l - 5513 \cdot V \cdot h - 5150 \cdot l \cdot h + 7875 \, V \cdot l \cdot h \quad (2)$$

Table 1. Plan matrix of a full factorial numerical experiment

No.	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$
1	+	+	+	+	+	+	+
2	-	+	+	-	-	+	-
3	+	-	+	-	+	-	-
4	-	-	+	+	-	-	+
5	+	+	-	+	-	-	-
6	-	+	-	-	+	-	+
7	+	-	-	-	-	+	+
8	-	-	-	+	+	+	-

Table 2. Factor variation intervals in a numerical experiment

Camera volume V, m³			Distance to burners l, m			The height of the opening for the removal of combustion products h, m		
The smallest value, V_{-1}	Average value, V_0	The greatest value, V_1	The smallest value, l_{-1}	Average value, l_0	The greatest value, l_1	The smallest value, h_{-1}	Average value, h_0	The greatest value, h_1
0.8	0.9	1	0.6	0.7	0.8	0	0.4	0.8

Table 3. Dispersion of temperatures on the heating surface of fragments of reinforced concrete building structures according to the results of a full factorial experiment

Experimental situation (Table 1)	1	2	3	4	5	6	7	8
S^2	958	1204	1366	1486	144	862	988	1328

Table 4. Regression coefficients for calculating temperature dispersion on the heating surface of fragments of reinforced concrete building structures

Coefficient	p_0,	p_1,	p_2,	p_3,	p_4,	p_5,	p_6,	p_7
Values (encoded)	1042	-178	-250	211,5	-63	86,5	77,5	31,3
Values (real)	4133	-2555	-1220	-800	-5513	-5150	7875	4221

Obtaining the regression dependencies made it possible to create a mathematical model of the furnace, which will ensure the reproducibility of the results of the experiments. It is necessary to model this furnace with the structural fragments inside and check the temperature distribution on their surfaces.
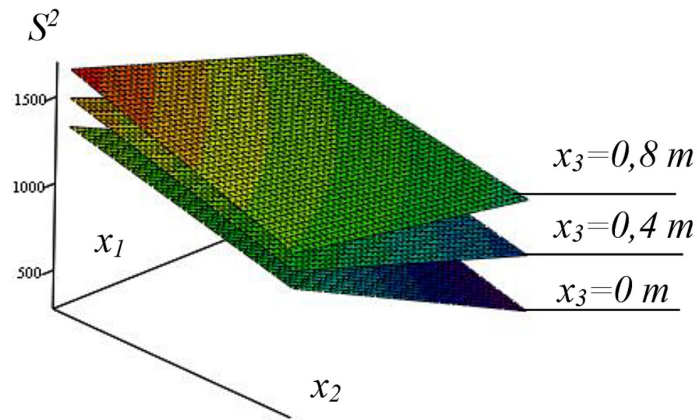
Figure 2. Dispersion of temperatures in the fire furnace chamber at a constant location of the opening for the removal of combustion products (factor 3) and variations of other factors
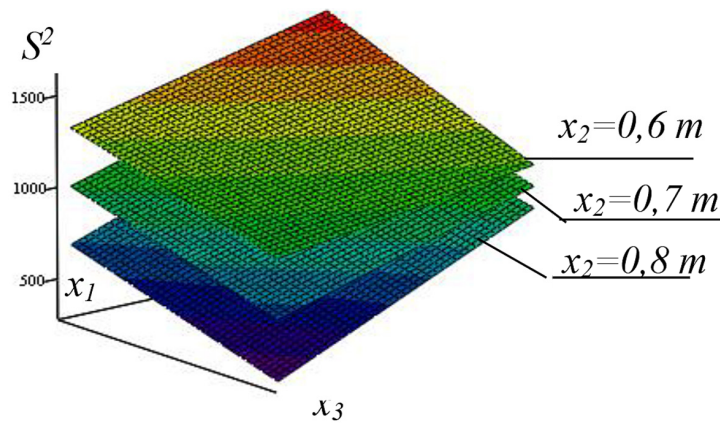
Figure 3. Dispersion of temperatures in the fire furnace chamber at a constant distance to the burners (factor 2) and variations of other factors
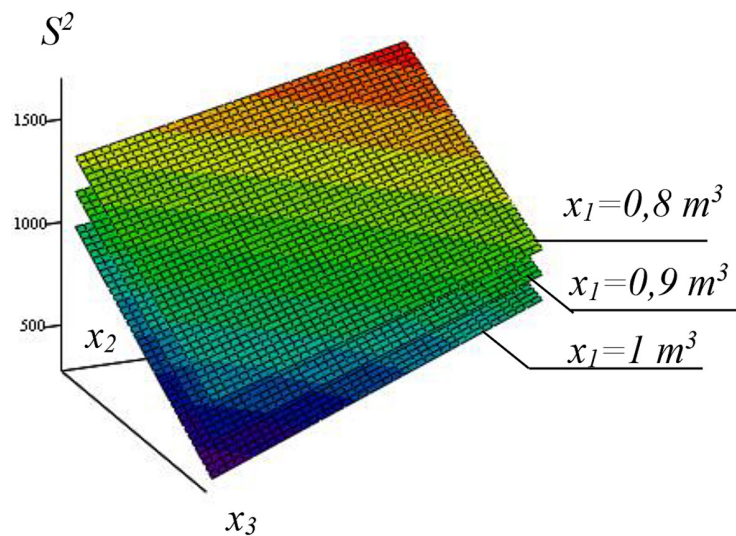
Figure 4. Dispersion of temperatures in the fire furnace chamber with constant volume of the furnace chamber (factor 1) and variations of other factors
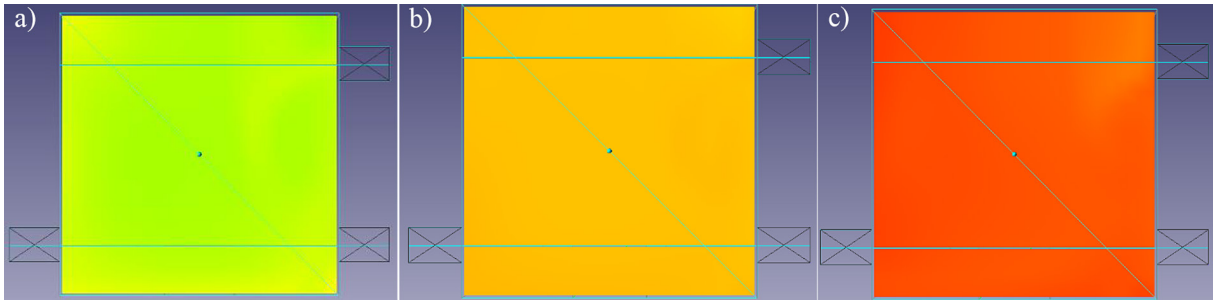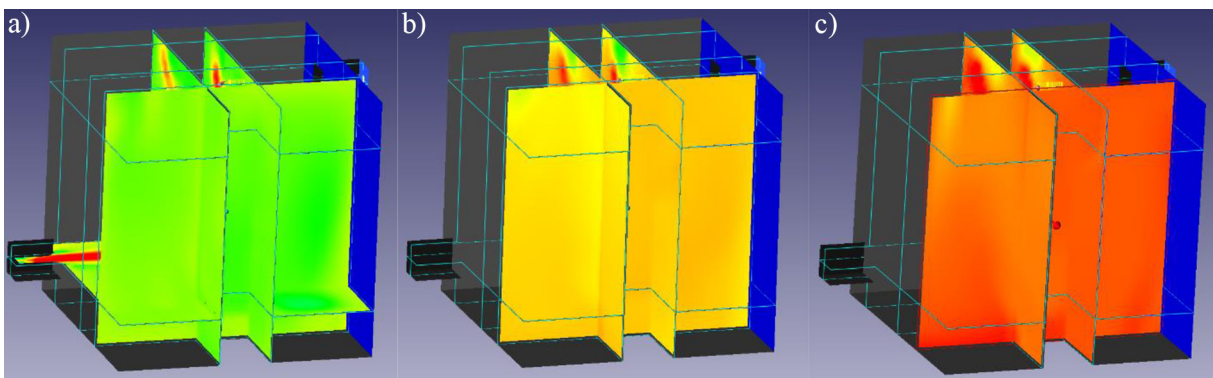
Figure 5. Temperature distribution on the heating surface of the wall during heating according to the standard fire temperature regime, (a) 10 minutes, (b) 30 minutes, (c) 60 minutes
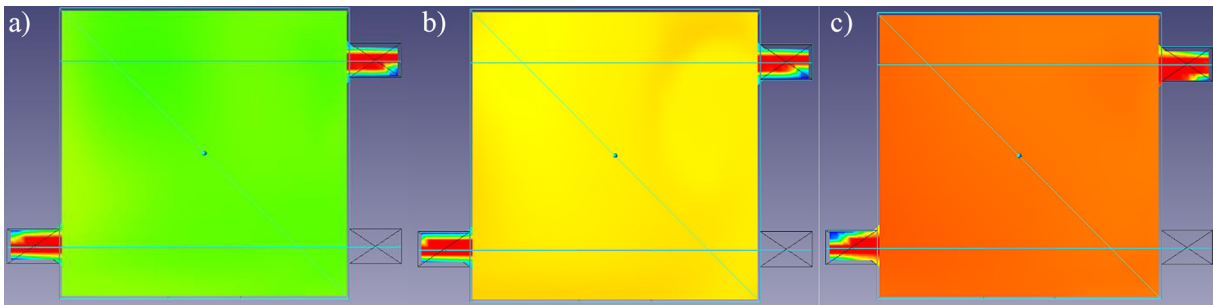
Figure 6. Temperature distribution on the heating surface of the plate during heating according to the standard fire temperature regime, (a) 10 minutes, (b) 30 minutes, (c) 60 minutes
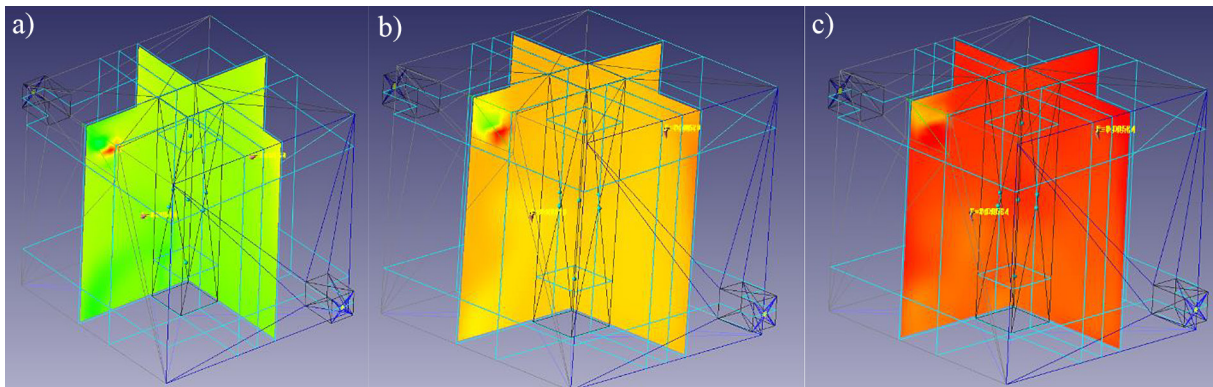
Figure 7. Temperature distribution on the heating surface of the beam during heating according to the standard fire temperature regime, (a) 10 minutes, (b) 30 minutes, (c) 60 minutes

Figure 8. Temperature distribution on the heating surface of the beam during heating according to the standard fire temperature regime, (a) 10 minutes, (b) 30 minutes, (c) 60 minutes

After conducting computer simulation, the results were obtained. Figures 5–8 show the distribution of temperatures on the surface of elements of reinforced concrete building structures when heated according to the standard fire temperature regime.

Analysis of the results of the calculations presented in Figures 5–8 lead to the conclusion that the universal installation ensures uniformity of heating and the possibility of reproducing the standard fire temperature regime.

For a more qualitative analysis of the work of the models, it was necessary to determine the numerical indicators of its work. Since the purpose of the creation was the study of the thermal effect on building structures, it is advisable to ensure the most possible uniformity of their heating, for the qualitative reproducibility of the data of real experiments.

Therefore, the value of temperature dispersion on the surface of each of the simulated structures of the furnace chamber was determined at each minute of the computational experiment, after which a graph of its change over time was drawn.

The CFD «FlowVision 2.5» computer gas-hydrodynamics tools created temperature fills on the heating surface of the structures (Fig. 5–8) and obtained the temperature distribution at each minute of the tests for each configuration. Based on the processed information, the temperature dispersion was calculated (Fig. 8).

According to the analysis of the obtained results (Fig. 9), the chosen configuration of the furnace chamber fully meets the requirements presented for the tests of building structures and is able to ensure the reproducibility of the results.

Therefore, the analysis of the created model proves that there is a slight dispersion on the heating surface of all types of elements of reinforced concrete structures, which does not affect the quality of its heating. According to the conducted computer modeling, it is possible to assert the sufficient accuracy of the selected configuration of the furnace chamber. Thus, it was possible to move from calculations to the development of sketches of a real installation with the parameters of the furnace chamber defined and verified in this section of the work.

On the basis of the obtained data, a sketch of the installation was developed for conducting the experimental part of evaluating the fire resistance of load-bearing reinforced concrete building structures under the influence of the standard fire temperature regime, which is able to ensure a high degree of reproducibility of experimental data.
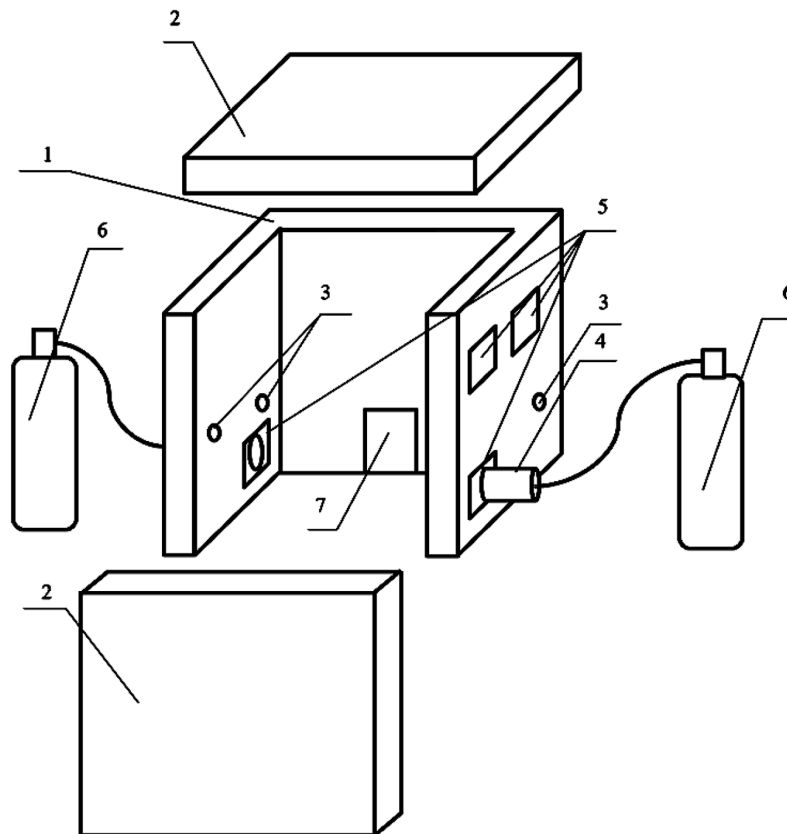
Figure 10 shows a diagram of the structure of a small-sized installation for the study of the thermal effect of fire on building structures.

A small-sized installation for studying the thermal effect of fire on building structures is used as follows: a fragment of a reinforced concrete structure is installed to the u-shaped enclosure of the furnace (1), depending on the type of structure under investigation, one or two removable panels (2) are used. Temperature sensors (not shown in the diagram) are installed in the holes for temperature control sensors (3) and in the test sample (not shown in the diagram). Next, the burners (4) are lit, which are installed in the holes for the burners (5) and with the help of gas supply from the gas cylinder (6) the set temperature regime is created in the middle of the furnace chamber.
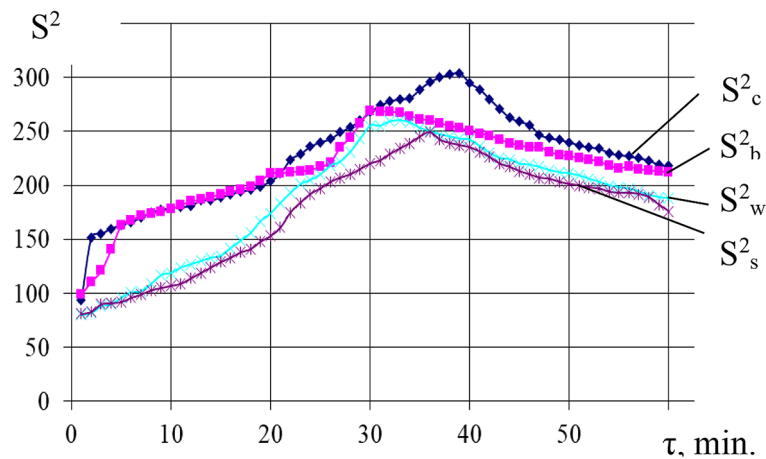
Figure 9. Dispersion of temperatures on the heating surface of elements of reinforced concrete building structures during computational experiments, S^2_c – columns; S^2_b – beams; S^2_w – walls; S^2_s – slabs

Figure 10. Sketch of a small-sized installation for studying the thermal effect of fire on building structures, 1 – u-shaped furnace enclosure, 2 – removable panels, 3 – holes for installing temperature control sensors, 4 – burners, 5 – holes for installing burners, 6 – gas cylinder with a regulating device, 7 – hole for removal of combustion products

In the lower part of the furnace chamber there is a hole for removing combustion products (7). The technical possibility of changing the size of the opening for the removal of combustion products is provided, which allows you to additionally regulate the heating process of the furnace chamber and the temperature regime of the fire. Control of the temperature of the tested samples is carried out with the help of special technical means (not shown in the sketch). The results of fire experiments are processed in accordance with current standards and developed methods.

CONCLUSIONS

According to the results of this work, the parameters of the fire furnace chamber and the location of its key elements are substantiated, which will have universality, compactness, high reproducibility of results and ensure environmental friendliness in comparison with large-sized installations due to the use of gas as fuel.

The regularities of the dependence of the temperature dispersion in the fire furnace chamber (S^2) from the volume of her chamber (V), the distance from the burners to the surface of the studied fragment of the load-bearing reinforced concrete building structure (l) and the height at which the opening for the exit of combustion products is located (h) were established as:

$$S^2 = 4221 + 4133 \cdot h - 2555 \cdot l - 1220 \cdot V - 800 \cdot V \cdot l - 5513 \cdot V \cdot h - 5150 \cdot l \cdot h + 7875 \, V \cdot l \cdot h \quad (3)$$

which made it possible to substantiate the parameters of the furnace chamber and the location of its key elements.

Computer modeling proved that to ensure the universality of the furnace chamber, it is necessary to create a cubic shape with internal dimensions of 1×1×1 m, and it is also necessary and sufficient to have 2 gas burners with variable placement to ensure the minimization of temperature dispersion on the heating surfaces of fragments of reinforced concrete constructions.

On the basis of the received data, a sketch of the installation was created for the experimental part of evaluating the fire resistance of load-bearing reinforced concrete building structures under the influence of the standard fire temperature regime, which can ensure a high degree of reproducibility of test results and increase their environmental friendliness.

REFERENCES

1. Bartlett, A.I., McNamee, R., Robert, F., Bisby, L.A. 2020. Comparative energy analysis from fire resistance tests on combustible versus noncombustible slabs. Fire and Materials, 44(3), 301–310. https://doi.org/10.1002/fam.2760

2. Demchyna B.G., Fitsyk V.S., Polovko A.P., Peleh A.B. 2006. Furnace for thermophysical tests of small fragments of building structures and individual nodes of their butt joints. Patent. 17160 Ukraine, F23M5/00. Bulletin, 9.

3. EN 1363-1:1999. Fire resistance tests – Part 1: General requirements.

4. ISO 834-1: 1999. Fire resistance tests – Elements of building construction – Part 1: General requirements.

5. ISO/IEC 17025:2005. General requirements for the competence of testing arid calibration laboratories.

6. Nuianzin O., Pozdieiev S., Borsuk O., Nekora O. 2021. Investigation of the Limit of Fire Resistance of a Steel Beam at Loss of Integrity of a Fire-Resistant Lining. In Materials Science Forum. Trans Tech Publications Ltd, 1038, 345–351. https://doi.org/10.4028/www.scientific.net/MSF.1038.345

7. Pozdieiev S., Nuianzin O., Binetska O., Borsuk O., Shvydenko A., Alimov B. 2020. Temperature effect on the thermal-physical properties of fire-protective mineral wool cladding of steel structures under the conditions of fire resistance tests. Eastern-European Journal of Enterprise Technologies, 4(12–106), 39–45. https://doi.org/10.15587/1729-4061.2020.210710

8. Schmid J., Klippel M., Just A., Frangi A. 2014. Review and analysis of fire resistance tests of timber members in bending, tension and compression with respect to the Reduced Cross-Section Method. Fire safety journal, 68, 81–99. https://doi.org/10.1016/j.firesaf.2014.05.006

9. Wickström U. 1994. The plate thermometer-a simple instrument for reaching harmonized fire resistance tests. Fire Technology, 30, 195–208. https://doi.org/10.1007/BF01040002