Development of a Mathematical Model of Fire Spreading in a Three-Storey Building Under Full-Scale Fire-Response Tests

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Abstract. The purpose of the work was to develop a mathematical model of fire spreading in a three-story building during full-scale fire-response tests; research of accuracy and reliability of parameters of temperature modes of fire in separate premises of the building. The Pyrosim computer system, a user shell for the Fire Dynamics Simulator program, was used to calculate the temperature in the models of premises under fire. A numerical experiment was conducted to model full-scale tests of premises with fire in a three-story building using computer gas-hydrodynamics methods. The nature of the fire development and the time dependences of its main parameters were revealed, which in turn allowed analyzing the adequacy of the modelling results and investigating their adequacy and accuracy. The obtained results of the research on the accuracy of modeling the full-scale tests of premises with fire in a three-story building revealed that the error, determined when comparing experimental and calculated data, was not significant. A relative error did not exceed 28%, and root-mean-square deviation did not exceed 51 °C. This means that the modeling results are adequate, which allows to use this approach for predicting the behavior of building structures in a fire under realistic conditions.

Keywords: Computer fire modeling · Fire resistance · Fire dynamics simulator · PyroSim · Field fire model

1 Introduction

1.1 Problem Statement

Fire safety of buildings and structures depends on an adequate estimation of fire resistance of their structures. A proper estimation of fire resistance of structures is possible only when using for calculations such temperature models of fires, which most accurately correspond to fire under realistic conditions.

Mathematical modeling of fire in premises involves the availability of data on the size of the premises, its openings, the density of fire load, the value of the maximum

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temperature of the fire and the time of its occurrence, and so on. Some research data are to some extent contradictory, due to differences in the objectives of particular researches. When carrying out the calculated estimation of fire resistance of building structures, taking into account the real thermal impact of fire, the analysis of the fire resistance problem is reduced to solving three separate tasks. These are the tasks of determining the temperature in a premise with fire near the structural elements; the task of calculating the temperature in the inner layers of structural elements and the task of thermopower response of structural elements to a given thermal impact.

The situation is complicated here by the need to use powerful commercial software, which requires appropriate qualified specialists and significant material costs for the license acquisition required for using this software. Another problematic issue for application of this approach is the need to consistently perform these steps in the absence of the possibility of using general mathematical relations to obtain the final result.

This will increase the productivity of calculations without indicating the advantages of this approach to the temperature modes of fires, namely greater accuracy and reliability with reduced rigidity of the requirements for fire resistance of the researched structures.

Elimination of the specified shortcomings of the approach of calculated estimation of fire resistance of the elements of building structures on the basis of the temperature modes of fires under realistic conditions, allows solving an actual scientific and technical problem.

1.2 Analysis of the Recent Studies and Publications

The research results of the temperature mode during a fire in a residential premise are described in [1–3]. Recently, quite popular became the use of special software – the Fire Dynamics Simulator (FDS) - for computer modeling of the results of tests of building structures for fire resistance.

This software allows to perform numerical simulations of the temperature distribution in structures during fire-response tests, as well as other parameters that are important for predicting the probability of progressive collapse in case of fire-caused damage [4–6].

The work [7] presents some results of several researches obtained using the FDS (version 4.0 Fire Dynamics Simulator), which are compared with experimental data. The aim of the work was to test the capabilities of the FDS program to model the flame spreading, as well as to determine the optimal values of the parameters of the combustible load of the material for the engineering use of the FDS. The authors of the works [8, 9] have researched experimentally and numerically the fire resistance of facade structures. The experimental setup modeled a three-story residential building. The numerical model was built in the CFD program by the FDS with similar geometry and instrumentation. The authors were able to properly reproduce the real test conditions in the model, but the temperatures close to the fire source could not be properly taken into account in the model.

The works [10, 11] compare the results of full-scale fire-response tests according to the Swedish (SP Fire 105) and British (BS 8414-1) methods. The presented results of experimental researches and computer modeling take into account different variations of fire exposure, fire load and the type of fire load. The modeling in the FDS made it possible to reproduce the experimentally determined temperature values both qualitatively and quantitatively.

In the work [12], fire dynamics models were performed using the FDS for two full-scale experiments conducted by the Efectis France laboratory. The main purpose of this research was to evaluate the ability of the numerical model to reproduce the quantitative results of temperatures and heat flux for further estimation of the characteristics of the impact of fire on the facade insulation. When comparing the experimental data with numerical calculations, there were obtained satisfactory results of temperature and heat flux.

The issue of fire resistance calculation is highly relevant, especially for the most widely used in the world reinforced concrete structures [13–18]. The problem of defects and damages in such structures significantly reduces fire resistance [19–22]. In particular, one of the most influential factors is the corrosion of reinforcement, which leads to structural defects and reduced performance [23–26]. Today there is the great variety of strengthening methods. Among the most popular are metal and reinforced concrete casing, as well as the external carbon tape, FRCM systems and other methods [27]. Similarly, this problem is typical for structures strengthened with external reinforcement. Additionally, interesting is the issue of fire resistance calculation for structures strengthened with reinforced concrete casing [28].

The authors of the works [29–31] investigated the influence of horizontal obstacles at different heights between unprotected openings on the facade of the building on the spread of external fire experimentally and compared the data using the numerical FDS instrument. It was concluded that the FDS version 6.2.0 can reproduce experimental results with a high level of detail. Authors of the work [32] attempted to reproduce the scenario of an external fire in facade insulation systems and proposed a method of quantitative assessment of the fire risk using the FDS software.

2 Purpose and Objectives of the Research

The purpose of the work is to develop a mathematical model of fire spread in a three-storey building during full-scale fire-response tests; a research of accuracy and reliability of the parameters of temperature modes of fire spread in separate premises of the building. To achieve this purpose, it is advisable to use the methods of computational gas-hydrodynamics, which allow determining the limits of application of this approach for predicting the behavior of building structures exposed to fire.

To achieve this purpose, the following objectives were set:

- to conduct a set of numerical experiments on the development and spread of fire in the premises of the full-scale model of a three-story building with the help of mathematical modeling by the methods of computer gas-hydrodynamics;
- to estimate the influence of factors of statistical error in the experiment on the basis of model results;

- to estimate the limits of application of this approach for forecasting the behavior of building structures in fire under realistic conditions, taking into account the obtained data of statistical error of the model results.

3 Materials and Methods of the Research of the Temperature Modes Parameters for Fire Development by Means of Mathematical Modeling

We used the Pyrosim computer system, a user shell for the Fire Dynamics Simulator (FDS) program, to calculate the temperature in the premises models in fire. This FDS system uses numerical algorithms to solve the complete system of the Navier-Stokes differential equations to determine the temperature and other dangerous factors during a fire [33]. The model results of these premises should be used to research the influence of the scale of premises' models in fire, the influence of automatic fire extinguishing systems and artificial ventilation systems.

To visualize the calculation results, the software module of the PyroSim Smokeview system is used. It allows building appropriate graphical representations for the temperature distributions. This system also allows monitoring the dynamics of temperature fields and reproducing the heating process with animation. This system also allows obtaining pictures of smoke condition, and the distribution of the concentration of combustion products [33, 34].

The FDS algorithms are based on the numerical solution of the Navier-Stokes differential equations, assuming that fire flows have a low velocity and dependence on temperature, with the corresponding patterns of formation. In this case, for the numerical approximation of differential equations of heat and mass transfer, the method of finite differences on regular grids is used according to the computational explicit scheme "predictor-corrector" of the second order of accuracy in coordinates and time [33, 34]. When modeling the premises with fires, it should be taken into account that the calculation grid is rectangular and this can affect the accuracy of calculations in curvilinear calculation areas [33, 34].

4 Results

4.1 Geometric Configuration of the Calculation Area

The Fig. 1 shows a geometric diagram of the calculation area in a three-story building.

The Fig. 2 shows a 3-D model with the location of temperature control points in the premises on the first (Fig. 2a) and second floor (Fig. 2b). The thermocouples were installed at a distance of 0.1 m from the inner surface of the wall, which were modeled in the software system. It is important to estimate the influence of the temperature of the fire mode on building structures. There were identified areas with thermocouples P1… P4, which are located at a distance of 0.1 m from the inner surface of the fencing

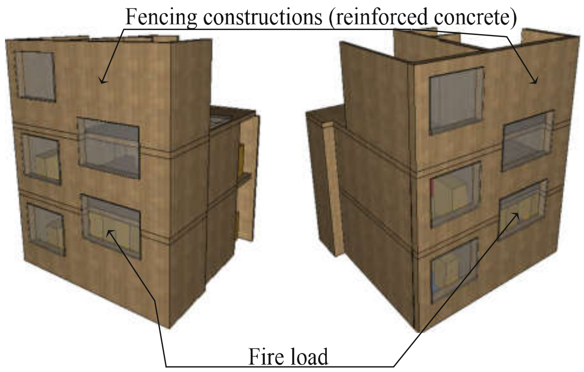

Fig. 1. Complete geometric diagram of the calculation area in a three-story building

constructions, according to which it was convenient to estimate the influence of the temperature field on the fencing constructions.

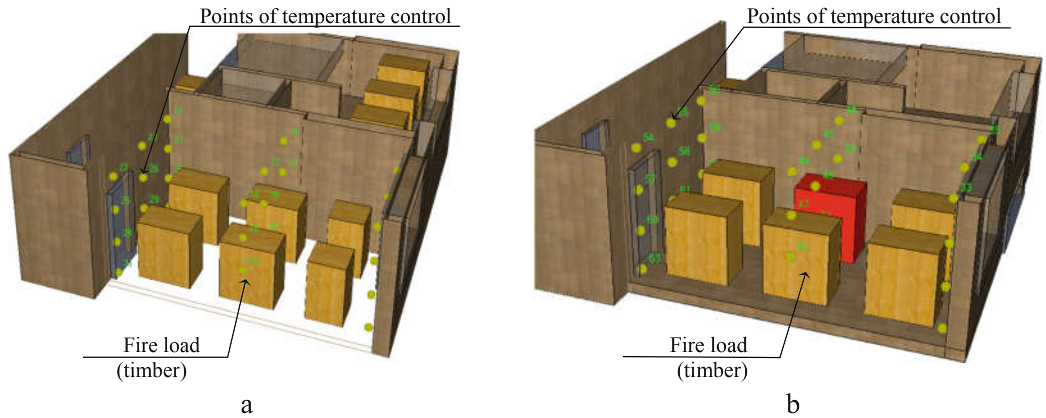

Fig. 2. Location of the point for recording the temperature indicators: a - on the first floor; b - on the second floor of the experimental building

4.2 Results of Temperature Calculation During a Fire in a Three-Storey Building

As a result of the calculation, the temperature distributions on the areas on the corresponding areas were obtained. The obtained results are shown in Fig. 4.

According to the temperature sensors (thermocouples), which were installed according to the schemes of location of thermocouples (Fig. 2), areas with thermocouples P1…P6 were identified and graphs of temperature dependence as a function of time were obtained. The results are shown in Fig. 5.

To research the reliability of the model results of temperature modes for full-scale tests in the premises of a three-story building, the main statistical parameters of the obtained data were researched. The data on the mean absolute deviations, mean relative deviations, mean square deviations of thermocouple indicators for the researched relevant tests are given in the Table 1. The data given in Table 1 showed that the error due to the difference between the calculated and experimental data reveals an

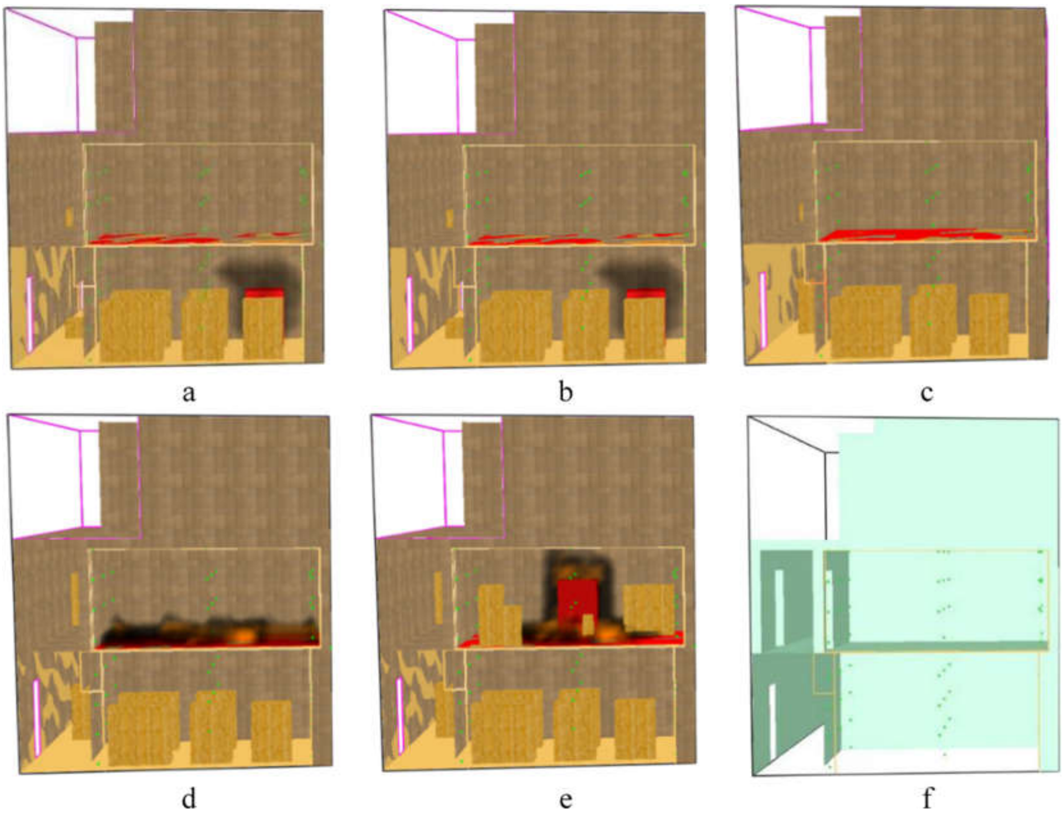

Fig. 4. The position of the flame jet of the fire at different moments of its development and spread in the section of the building: a - 600 s; b - 1200 s; c - 1800 s; d - 2400 s; e - 3000 s; f - 3600 s

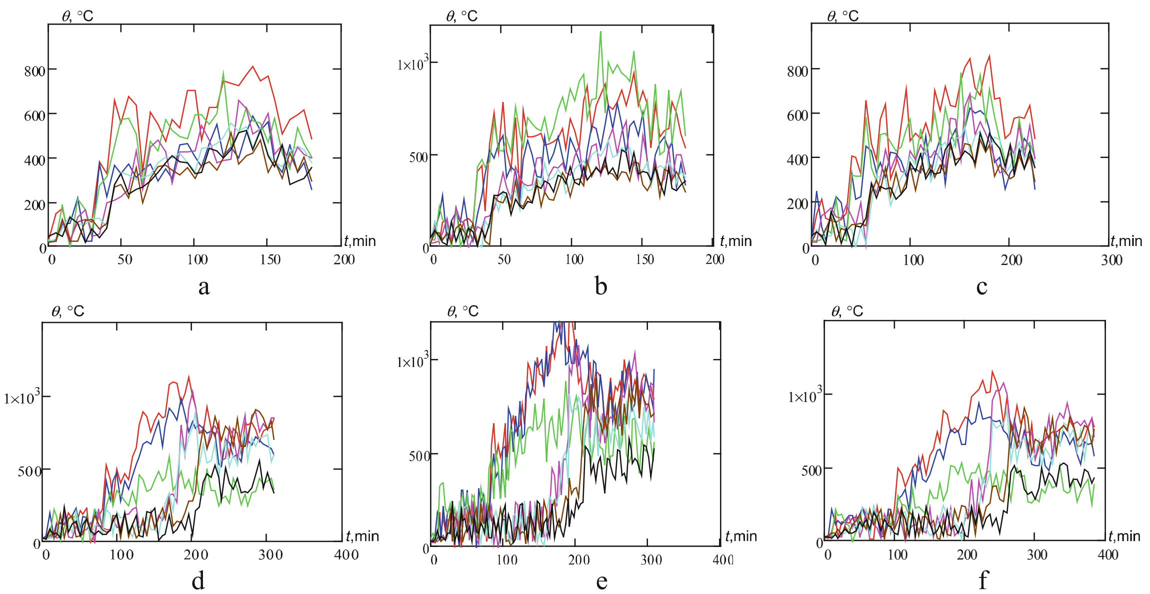

Fig. 5. Temperature indicators in the measured areas: a – 1; b – 2; c – 3; d – 4; e – 5; f – 6

acceptable accuracy of the determined mean volume temperature by mathematical modeling, since the relative error does not exceed 28% and the square deviation does not exceed 51 °C. This means that the temperature modeling results for full-scale tests in a three-story building are sufficiently accurate.

Table 1. Absolute deviations, relative deviations, square deviations of temperature modes compared with the experimental data

№ n/o	Position of the premise	Absolute deviations, °C	Relative deviations, %	Mean square deviations, °C
1.	The first floor	130.1	24.8	56.4
2.	The second floor	145.5	27.4	44.8
Mean values		137.8	26.1	50.6

The data on statistical criteria of temperature indicators for the corresponding series of tests are given in the Table 2.

Table 2. Statistical criteria of temperature indicators of model results of full-scale tests

№ n/o	Position of the premise	Cochrane's criterion	Student's criterion	Fisher's criterion
1.	The first floor	0.96	0.69	1.002
2.	The second floor	0.98	0.84	1.008

The results given in the Table 2 showed that the values of statistical criteria, due to the difference between the calculated and experimental data, do not exceed the tabular values. This means that the modeling results are adequate.

To verify the adequacy of the obtained results, the trend lines of the dependence of the medium-volume temperature on time and the corresponding variances of the deviations were built.

The built graphic dependences are given below in Fig. 6.

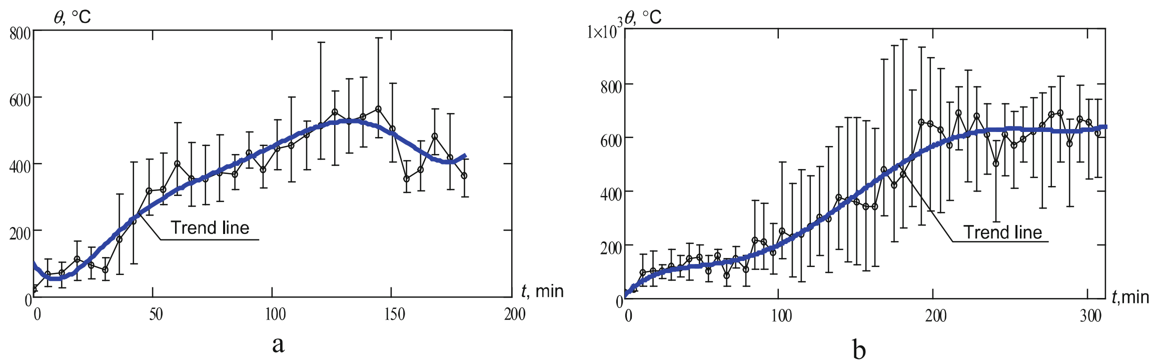

Fig. 6. Graphs of dependences of medium-volume temperature on time and corresponding variances of deviations for the premises: a - on the first floor; b - on the second floor.

5 Conclusions

There was conducted a numerical experiment on modeling full-scale tests of premises with fire in a three-storey building with application of methods of computer gas-hydrodynamics. The identified spread of fire and the time dependences of its main parameters were revealed, which in turn allowed analyzing the adequacy of the modeling results and researching their adequacy and accuracy.

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