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Investigation of the Temperature Impact of Fire through the Window Opening of a House with a Flammable Facade on Elements of Adjacent Objects

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Abstract. At present, the process of heat transfer as a possible criterion for determining the fire distances between buildings is insufficiently studied. In this regard, to justify the value of the fire distance between buildings, one of the possible options is to create an appropriate mathematical model. On the basis of gas dynamics methods, a mathematical model of the processes of the thermal effect of a fire through the window opening of a building with a combustible facade on the elements of adjacent objects has been developed. It is shown that its solution can be implemented in the FDS software package with acceptable convergence in comparison with experimental studies. It was found that the data of mathematical modeling are as close as possible to the averaged data of the experiment. Dependences of temperature changes on the time of fire exposure on samples and distance from the source of heat exposure were determined. The obtained data can be used to substantiate fire-prevention distances between buildings and structures due to the mathematical model of heat transfer between objects during a fire using gas dynamics methods, as well as during the substantiation of the algorithm for creating a mathematical model.

INTRODUCTION

With the development of new approaches for the design of buildings and structures, there is a need for parametric rationing of fire distances by studying the processes of heat transfer using methods of mathematical modeling. Some of these methods are considered in [1 - 7], where the processes of thermal efficiency of buildings, heat transfer during fires, heat and moisture transfer in building structures, etc. were studied. However, in these works, the heat transfer processes are not considered as a criterion for determining the fire distances between buildings. Therefore, research on the creation of a mathematical model to substantiate the value of the fire distance between buildings and its verification is quite relevant.

Purpose of this Paper

The purpose of this work is to develop a mathematical model of the processes of thermal impact of fire through the window opening of a house with a combustible facade on the elements of adjacent objects by the methods of gas dynamics and its validation with experimental data.

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Research Objectives

To achieve this purpose, the following problems should be solved:

- experimental determination of data on temperature change on the surface of the facade of the building from the thermal effects of fire in the adjacent building with the facade made of wooden materials;
- processing the obtained experimental data;
- gradual creation of a mathematical model of heat exchange during a class A fire in a building with a combustible facade on the elements of adjacent objects, using the software package FDS;
- conducting experimental research of the thermal effect of the flare of the model fire of class A on the elements of adjacent objects;
- checking the adequacy of the developed mathematical model.

MATERIAL AND METHODS

According to the results of the analysis of literature sources [8 - 11] it is established that today the assessment of fire distances is based on two criteria that ensure the safety condition: heat flux and temperature. However, the approach based on the use of the criterion of "heat flux" has a drawback, because today there is no sufficient statistical base of critical values for heat flux for various substances and materials. In addition, heat flux is not a direct quantity that can be associated with the causes of the spreading and fire coverage of adjacent buildings. It limits the possibility of using this criterion, therefore, to assess the fire distances, it is proposed to use a criterion that provides a condition for direct fixation of the possibility of fire on an adjacent house, taking into account the nature of its materials, namely, the ignition temperature of materials. Based on this, further research in the work is being built.

THEORY/CALCULATION

Experimental Research

Experimental studies were conducted to solve one of the problems. The essence of the method of this study was to simulate a fire in a building with a facade made of wooden materials (Fig. 1).

(a) (b)

FIGURE 1. Photo of a fragment of the house simulating the fire load (a) and a photo of a fragment of experimental research (b).

The burning fire load is located in the premises of a fragment of the building and in the structural elements of its facade, which is made of wooden materials. For the facade of the adjacent building, which is exposed to the combustion center, we used the studied samples of wood, which mimicked a fragment of the building and had dimensions of 250 mm × 250 mm × 250 mm. The humidity of the samples did not exceed 12 %, the tests were performed at a temperature of 10 °C, atmospheric pressure 101 325 PA, relative humidity of 60% and a wind speed of 1.5 m/s. At the same time, during the entire period of experimental research, no changes in the climatic factors of the external environment were recorded. Thermocouples were placed on the surface of the investigated samples, directed towards the combustion center, which in turn were installed at the level of the lower edge of the window opening of the house fragment and at distances of 2, 4, 6 m, respectively, along the central axis of the window opening and the house fragment edges. The test samples were placed according to the scheme (Fig. 2) [12].

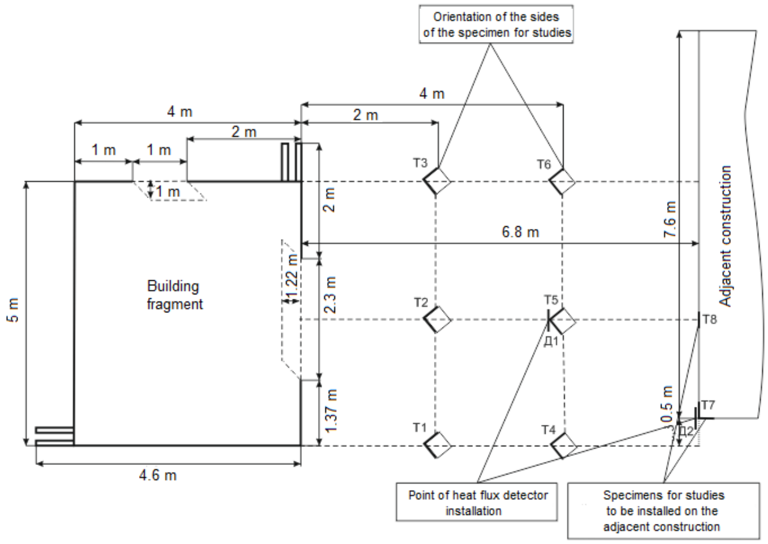


FIGURE 2. Scheme of arrangement of samples and measuring devices: T1 - T8 - place of installation of thermocouples.

According to the results of the experiments, the data on the temperature change on the surface of the studied samples depending on the distance of their location from the combustion center and the duration of thermal exposure were obtained. Figure 3 shows data on the change in surface temperature of the studied samples T2, T5 and T8.

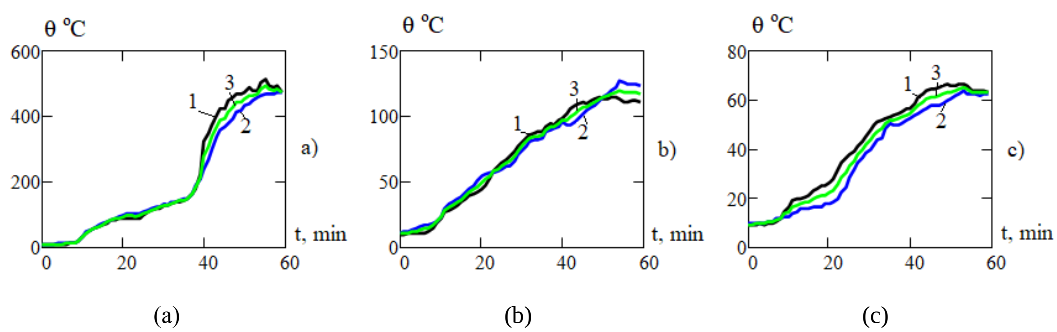


FIGURE 3. The dependence of the surface temperature of the test specimens on the distance of their location from the combustion center and the duration of thermal exposure: (a) data for the test sample T2, (b) data for the test sample T5, (c) data for the test sample T8 (1, 2 - data of a separate experiment), (3 - averaged data).

Checking the Affiliation of the Obtained Experimental Data to One General Population

The maximum absolute, relative and standard deviations of temperature values are calculated for the entire duration of thermal exposure. It was found that the absolute deviations of the experimental data of each experiment from the average values do not exceed 12.6°C, which is a percentage of 19.8 %, and the maximum standard deviation is 7.4°C, which indicates a satisfactory convergence of the obtained experimental data.

We checked the belonging of the data obtained in each experiment to one general population according to Fisher's criterion and determined the temperature dispersion (S) of the experimental data from the mean value according to the equation [13]:

$$S^2 = \frac{1}{n-1} \sum_{i=1}^{n_i} \left(\theta_i - \overline{\theta}_i\right)^2 \tag{1}$$

Figure 4 shows the dispersion of temperatures from the duration of thermal exposure, as an example we take the test sample T2.

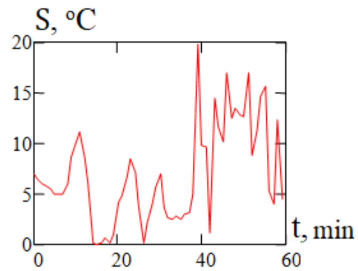


FIGURE 4. Dispersions of temperatures from the duration of thermal exposure for the test sample 2.

Development of a Mathematical Model

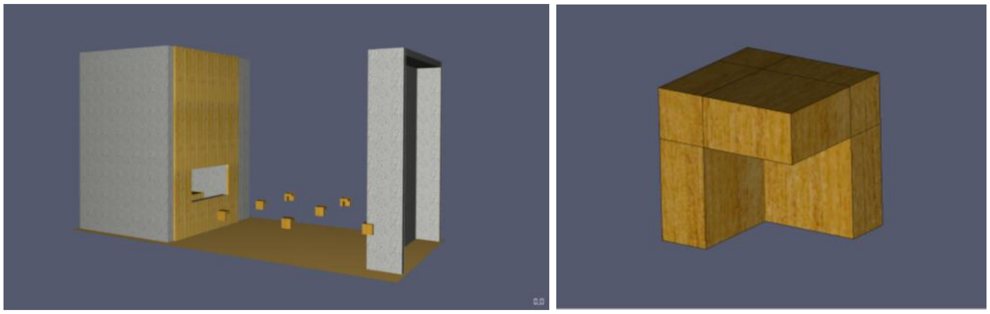
Mathematical modeling of the processes of thermal influence of the fire torch on the elements of adjacent objects by the methods of gas dynamics and experimental studies were performed according to the method [12].

Based on the proposed algorithm of actions in [14] a mathematical model was developed. The characteristics of the mathematical model are given in the table 1.

TABLE 1. Characteristics of the developed mathematical model.

№	Characteristics	Characteristic data
1.	General mathematical model	Basic Navier-Stokes equations for low-velocity temperature-dependent flows.
2.	Combustion model	Equations describing combustion in a two-phase flow of air and liquid fuel particles. Combustion is a generalized chemical hydrocarbon equation $C_xH_yO_z$ (C_6H_6O). In this case of the model, the combustion of a single substance, namely diesel, is considered.
3.	Chemical reaction	$C_xH_yO_z+(x+0.25y-0.5z)O_2 \xrightarrow{W} CO_2+0.5yH_2O$
4.	Solution	The solution to the basic equations of heat transfer between objects during a fire is to approximate the calculation area using an adaptive locally shredded mesh. As a result of a series of successive iterations, we have obtained the values of the analyzed functions at a certain point in time.
5.	Turbulence model	Turbulence is modeled using Smagorinsky's "Large Eddy Simulation" (LES) model.
6.	Radiant heat transfer	A diffusion model of gas radiation was used to account for radiant heat exchange in a gaseous environment and mutual heat exchange between the environment and particles, as well as solid material. This model is based on the assumption that the optical environment is isotropic.
7.	Modeling of flows and particles	The Lagrange particle method is used to account for heat and mass transfer during a fire.
8.	Dimensions of the calculation mesh	The dichotomy method was used to substantiate the dimensions of the mesh of the calculated mathematical model. The reasonable size of the cells is 10 cm × 10 cm.
9.	Simulation objects	1) Model fire pit of class 55B, which is a metal pan with a diameter of 1480 ± 15 mm, side height 150 ± 5 mm and wall thickness of 2.5 ± 0.5 mm, which is filled with 18 liters of water and 37 liters of diesel fuel; 2) the investigated wooden sample from a continuous pine bar in the sizes of 50 mm × 50 mm × 4000 mm; 3) diesel fuel
10.	Fuel mass loss rate	$m_n^{n(t)}=m_{f,0}^{n}(t)e^{-\int k(t)dt}$
11.	Temperature measurement	Sensors (thermocouples) are installed on the surface of the tested wood sample to measure the temperature.

The general view of the mathematical model and the studied sample is shown on Fig. 5.



(a) (b)

FIGURE 5. Mathematical model: (a) general view, (b) sample.

In the process of creating a mathematical model, a calculation mesh is created in the system of which calculations are performed.

The number of created cells of “multiple grids” is 485112 (Fig. 6).

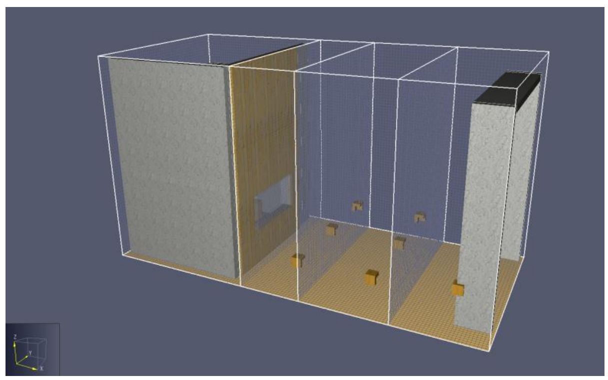


FIGURE 6. Type of calculation mesh of the mathematical model.

Creating scale objects is the next step in modeling.

The layout of the sensors in the mathematical model on the studied samples is shown on Fig. 7.

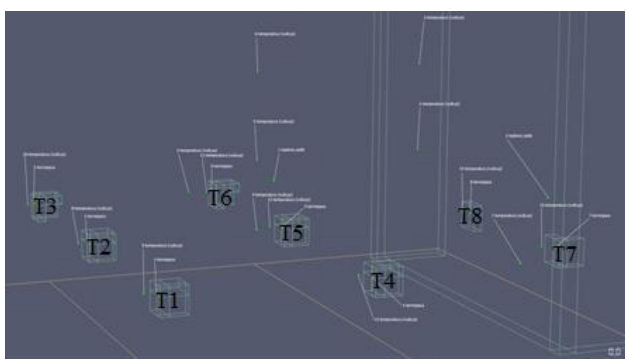


FIGURE 7. Location of sensors in the mathematical model of the studied samples (T1 - T8 place of installation of temperature measuring sensors).

The following procedures were performed in the simulation of combustion: creation of the combustion reaction in the gas phase, creation of a surface of the "burner" type, creation of an object with assignment of the created surface to it.

The fire load in the fire chamber is taken similar to that in [14].

The parameters of the fire load of the stack of bars, laid down in the mathematical model, are shown in the table 2.

TABLE 2. Fire load parameters for wood.

№	Parameter	Indicator
1	Specific heat dissipation, kW / m^2	78
2	Lower heat of combustion, kJ / kg	13800.0
3	Linear flame speed, m / s	0.0585
4	Specific mass burnout rate, kg / $m^2 \cdot s$	0.00630
5	Smoke-generating capacity, $Np \cdot m^2$ / kg	61.00
6	Oxygen consumption, kg / kg	1.1500
7	Ignition temperature, ^oC	250

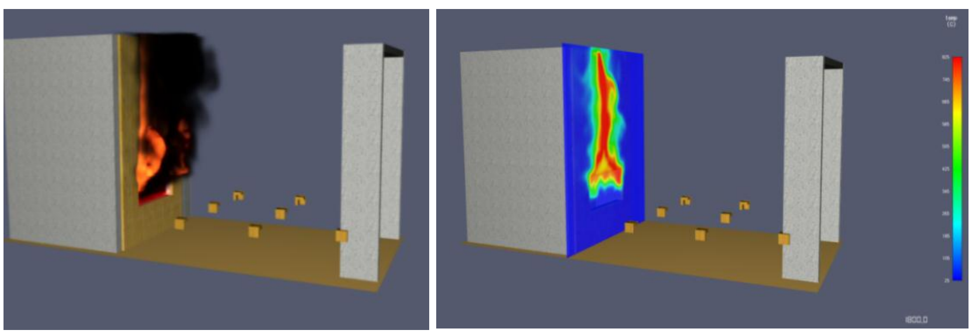
Gas evolution: carbon dioxide (CO_2) 3.16300 kg / kg; carbon monoxide (CO) 0.12200 kg / kg; hydrogen chloride (HCl) 0.00000.

The parameters laid down in the mathematical model for diesel fuel and materials are taken similarly to the work [14].

The final stage of modeling is the programming of general parameters, namely the required duration of modeling, environmental parameters, determination of limit values, which must be further determined during the calculation [12]. In this case, the environmental parameters embedded in the mathematical model are similar to those that developed during the experimental studies and did not change during the entire modeling period.

The total simulation time is set to 60 minutes.

The dynamics of fire development, as well as temperature visualization with the reflection of temperature fields is shown in Fig. 8.



(a) (b)

FIGURE 8. Model: (a) fire development, (b) design temperature after 60 minutes.

RESULTS AND DISCUSSION

During the simulation process, the dependence of air temperature on time in the volume of the fire chamber was obtained (Fig. 9).

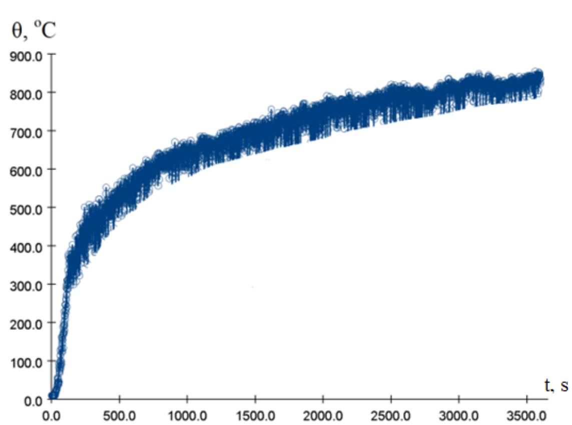


FIGURE 9. Dependence of air temperature on time in the volume of the fire chamber.

The results of mathematical modeling in comparison with the results of experimental studies conducted on the basis of [12], are presented in the form of graphs in one coordinate system for thermocouples T3, T5, T8. The results of the comparison are shown on Fig 10.

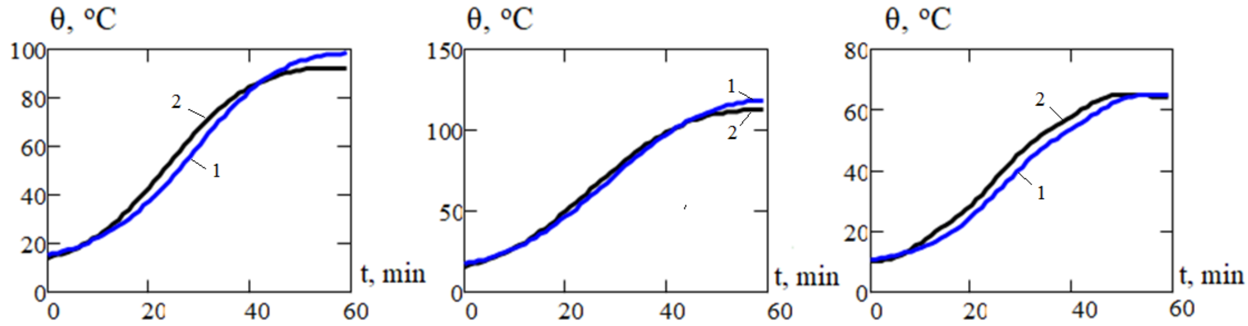


FIGURE 10. Comparison of mathematical modeling with the results of experimental research: (a) data for the test sample T2, (b) data for the test sample T5, (c) data for the test sample T8 (1 - modeling, 2 – experiment).

Adequacy was checked according to the following criteria: absolute deviations, relative deviations, standard deviations. The results of checking the adequacy of the developed mathematical model are shown in the table 3.

TABLE 3. The results of checking the adequacy of the developed mathematical model.

№	**№ thermocouples**	**Absolutely deviation**	**Relative deviation**	**RMS deviation**
1.	T1	4.853	18.581	5.722
3.	T3	4.863	10.004	6.285
4.	T4	6.468	12.932	7.599
5.	T5	3.738	8.431	4.62
6.	T6	4.00	13.744	4.297
7.	T7	4.533	14.641	4.837
8.	T8	3.154	9.589	3.586

Thus, the absolute deviations between the results of mathematical modeling and the average experimental studies do not exceed 7°C, the percentage does not exceed 20%, the standard deviations are within 3 ÷ 8 °C, which indicates that the mathematical modeling data are as close as possible to the average experimental data.

CONCLUSIONS

An experimental determination of data on the change in temperature on the surface of the facade of the building from the thermal effects of fire in an adjacent building with a facade made of wood is carried out. The obtained data were processed according to the absolute, relative, standard deviation and Fisher's criterion. The test showed the general convergence of the experiments. Using the FDS software, a mathematical model of heat exchange during a fire in a house with a combustible facade and elements of adjacent objects was created. It is shown that its solution can be implemented in the FDS software package with acceptable convergence in comparison with experimental studies. The dependences of temperature change on the time of fire action on the samples and distance from the heat source are determined.

The adequacy of the created mathematical model was checked. It is shown that the absolute deviations between the results of mathematical modeling and the average experimental studies do not exceed 7°C, that the percentage does not exceed 20%, the standard deviations are within 3 ÷ 8°C, which indicates that the mathematical modeling data are as close as possible to averaged experiment data.

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