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DETERMINING THE INFLUENCE OF FACADE PARAMETERS AND THE WIDTH OF A FIRE-PROOF EAVES ON PREVENTING THE SPREAD OF FIRE THROUGH EXTERNAL VERTICAL STRUCTURES OF BUILDINGS

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The object of this study is the process of fire propagation through the surface of external wall structures with facade thermal insulation. The paper examines the influence of facade parameters and the width of a fire-proof eaves on preventing the spread of fire by external vertical structures using the example of a residential building. With the use of FDS modeling, the relationships between the parameters of external enclosing structures and the fire-proof eaves on the processes of limiting the spread of fire were investigated. The influence of the minimum parameters of the height of the inter-floor windowsill in the absence of a fire-proof eaves on the spread of fire was determined. The dependence of temperature change near the surface of the facade on the width of the fire-proof eaves and the height of the window between floors was established.

Based on a series of simulated experiments, it was established that with a height of 1.0 m between floors and the absence of a fire-proof eaves, the critical temperature value is 250 °C. This value corresponds to the destruction temperature of a standard metal-plastic window structure. For the case when the wall height is 1.0 m, and the width of the fire-proof eaves is 0.75 m, the temperature value is 180 °C. That is, the safety condition of 250 °C is met.

Based on the research, a dependence was found on the criterion of not exceeding the critical temperature of 250 °C at the level of 1.4 m of the facade of the building floor located above the fire floor. The criterion holds when the width of a fire-proof eaves is at least 0.4 m and the height of the window partition is 1.0 m, as well as when the width of the eaves is 0.5 m, and the height of the window partition is 0.6 m.

It was established that the height of a window interfloor partition has a smaller effect than the width of the fire-proof eaves that separates the floors that are located above

Keywords: FDS modeling, thermal insulation, fire-proof eaves, interfloor partition, critical temperature, fire propagation

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1. Introduction

The use of fire-proof eaves as a facade fire barrier is one of the basic measures provided for by state building regulations DBN V.1.1-7:2016 «Fire safety of construction objects» and DBN V.2.2-41:2019 «High-rise buildings. Basic provisions». Satisfying the conditions for limiting the spread of fire on the facades of buildings, as well as meeting the requirements and safety indicators of buildings and structures related to their essential operational characteristics are regulated by requirements [1]. It should be noted that the use of fire-proof eaves is possible not only for high-rise construction but also for multi-story buildings and facilities with increased stories, which are divided into several vertical fire compartments. As an example, such cases are typical for residential, public, and administrative buildings, in which it is possible to place built-in premises of a different functional purpose (shops, cafes, institutions providing social services, etc.). Fig. 1 shows an example of such buildings equipped with a fire-proof eaves that separates vertical fire-proof compartments.

a *b*

Fig. 1. Examples of buildings equipped with fire-proof eaves: *a* – residential; *b* – public

The only method that regulates the installation of a fire-proof eaves in accordance with building codes and standards is administrative. That is, there is only a description of this object of regulation in construction (design parameters, requirements for materials, etc.), which does not provide an alternative to this solution.

To ensure the requirement to limit the spread of facade fire, there is no description of the criterion that clarifies the goals of the regulatory provision.

In fact, the only requirement for the parameters of fire-resistant eaves is its width protruding beyond the facade, as well as a fire resistance class of at least EI 90. This approach does not allow evaluating the effectiveness of the proposed measure for one or another type of facade, as well as taking into account its actual fire hazard. At the same time, the parameters of facade systems and external enclosing structures can significantly influence the processes of fire propagation, both in terms of its limitation and vice versa – to be the cause of its rapid spread to higher floors and fire-resistant compartments [2–5].

Examples of the most high-profile fires indicate the problems in ensuring fire safety of the structures of the external walls of buildings and structures with facade thermal insulation both at the construction stage and during their operation. Such fires are caused not only by gross violations of fire safety rules but also by the use of building and finishing materials with increased fire hazard [6]. It should be noted that typical fires have a low frequency of occurrence, but the consequences associated with them (area of fire propagation, material damage, injuries and death of people) can be significant.

The key issue related to the installation of fire-proof eaves is that in the current building regulations, regardless of the parameters of the window interfloor partition, the size of eaves remains unchanged. It is 0.3 m or 0.75 m, depending on the conditional height of the building and its functional purpose, and is adopted exclusively by the regulatory method of rationing. Thus, it is a relevant task to investigate the structural parameters of the facade of a residential building and their influence on the processes of limiting the spread of fire through the surface of external wall structures with facade thermal insulation.

2. Literature review and problem statement

Work [7] reports the results of several studies using the FDS program (version 4.0 Fire Dynamics Simulator), which are compared with experimental data. The purpose of the work was to check the capabilities of the FDS program for modeling flame propagation, as well as to determine the optimal values of the parameters of the combustible load material for the engineering use of FDS. Experimental studies included testing according to ISO 5660-1:2015, as well as full-scale fire propagation tests according to ISO 9705-1:2016. In [8], the problems related to the fire hazard of external wall structures with facade thermal insulation and plastering were considered. Full-scale fire tests were carried out on the structure of the external wall with facade thermal insulation, equipped with plaster for the spread of fire, where PSB-S-25 polystyrene foam with an average thickness of 150 mm was used as a thermal insulation material. Computer simulation of fire dynamics using FDS was performed, and numerical results were compared with experimental data to verify the software's ability to reproduce real fire conditions in residential buildings. Experimental studies were carried out according to a standardized methodology, which involved determining the extent of damage to the thermal insulation and finishing system and the increase in temperature inside it due to fire action. However, the studies did not take into account variations in the parameters of the facade and the presence of a fire barrier, which is due to the procedure of full-scale fire tests.

In works [9, 10], the fire resistance of facade structures was investigated experimentally and numerically. The experimental setup simulated a three-story residential building with an external thermal insulation and finishing system. The authors managed to properly reproduce the real test conditions in the model, but the temperatures close to the real fire conditions could not be properly reproduced. The reason for the discrepancies in the temperature values was the difficulties associated with the reproduction of the model fire in FDS.

In work [11], the dynamics of fire development on a test bench for facade structures were experimentally and numerically investigated. The experimental setup simulated a three-story residential building (6.7 m high, 4 m wide, and 1.6 m deep) with exterior wall cladding. A numerical model was developed in the Fire Dynamics Simulator (FDS) program with similar geometry and measurement equipment. Research was conducted for external wall structures with facade thermal insulation for two different types of wall cladding. However, technical solutions to prevent the spread of fire through the surface of the facade of the building due to the unchanged geometry of the window opening of the test bench and the impossibility of changing the configuration of the facade systems were not investigated in the work. This was predetermined by the test methodology.

The general features of the fire test were well reproduced in the numerical model; however, the temperatures near the fire source could not be properly reproduced. The reason for this was that the obtained temperature values of the numerical model were significantly overestimated due to radiation errors.

Work [12] gives a comparison between full-scale facade tests, which were conducted according to the Swedish SP Fire 105 [13] and the British BS 8414-1 [14] procedures. The authors tried to reproduce the repeatability of the results of experimental studies in a numerical model and use computer simulation to determine the impact of changes in the experimental setup during the research. The reported research results took into account different variations of fire exposure, fire load, and type of fuel. FDS modeling did not allow the authors to fully reproduce the experimentally determined temperature values qualitatively and quantitatively. But it was concluded that the use of computer simulations can reduce the volume of large-scale tests, which are accompanied by large economic costs.

However, the authors did not investigate the influence of fire barriers on the effectiveness of preventing the spread of fire through the surface of the facade system, which is explained by the technical characteristics of the test facilities. The results of the experimental studies showed that the reproducibility of the results, both in the BS 8141-1 procedure and in the SP Fire 105 procedure, is questionable. The reason for this was the different types of fuel (wood and heptane) used in the research process, as well as the different geometry of the combustion chambers. Thus, it was impossible to control the thermal effect on the surface of the facade, which differed due to various factors (thickness of the test samples; the movement of air currents, which affected the temperature values), etc. In order to provide a reliable, repeatable, and reproducible method of testing facades, it was necessary to solve these problematic issues.

In [15], the facade system was tested according to the methodology required by the French technical specification LEPIR 2-2010 «Facade fire propagation test». It is aimed at limiting the risks of fire propagation through the facades to the upper levels. Fire dynamics simulations were performed using FDS for two full-scale experiments conducted by the Efectis France laboratory. The main goal of the study was to evaluate the ability of the numerical model to reproduce the quantitative results of gas temperatures and heat flow on the tested facade for the further assessment of the characteristics of the effect of fire on the facade thermal insulation. Satisfactory temperature and heat flux (HRR) results were obtained when comparing experimental data with numerical calculations. The studies did not take into account the possible change in the heat flow values, which is explained by the lack of the possibility of using different types of model fires. To limit the risks of fire propagation, the angle of inclination of the facade plane was not investigated, which is explained by the design features of the facade test bench.

In [16], the results of studies into the impact of structural parameters of the facade fireproof eaves on the boundaries of fireproof compartments on the prevention of the spread of fire in high-rise buildings using FDS-modeling are reported. The findings showed that the presence of a fire-proof eaves actually reduces the actual temperature at the level of the upper floor under which the fire started by 45–47 %. However, the questions of investigating the influence of the parameters of the inter-floor window wall in the presence or absence of a fire-proof eaves on the spread of fire remained unresolved.

Works [17, 18] report the results of studies into the influence of the balcony effect on the spread of flames through external windows to the higher floors. Three configurations above the window opening were investigated: no balcony, with a balcony of the same width as the window opening, and with a balcony 1 m wider on each side of the window opening. The live fire tests were numerically simulated using FDS. The results of experimental and numerical research methods were compared. Conclusions were drawn and the most effective structural solution was proposed to limit the spread of fire through the surface of facade systems.

In [19], a numerical analysis was performed to assess the impact of fire obstacles on the spread of fire through ventilated facades. The presence of vertical obstacles had a positive effect on preventing the spread of fire, as the insulation behind the vertical obstacle remained intact. Vertical obstacles delayed the horizontal propagation of fire depending on the type of insulation. The test results became the basis for future studies on the influence of fire barriers on the spread of fire through the surface of facade systems.

The impact of passive measures to prevent the external vertical spread of fire was investigated using the FDS tool in [20]. The numerical study was divided into a validation study and a comparative analysis. The results reported by the authors show that the arrangement of facade structures with a horizontal fireproof eaves with a width of 60 cm provides better fire protection compared to a structure without an eaves.

The purpose of paper [21] was to investigate and compare the effect of horizontal eaves between unprotected window openings on the building facade. FDS version 6.2.0 was shown to be well suited as a calculation tool for this task given the parameters presented. The main findings were that the use of horizontal eaves with a width of at least 60 cm leads to less consequences and lower levels of risk on the facade during a fire. Modeling of horizontal eaves with a width of 20 cm and 30 cm did not give satisfactory results. The use of horizontal eaves with a width of 60, 80, and 100 cm led to a decrease in the surface temperature on the facade 1.2 m above the window opening by 15–50 %.

Our review of foreign building regulations and scientific studies on the effectiveness of fire-proof eaves revealed the lack of recommendations or a single approach regarding the design parameters of fire-proof eaves, which are expected on the facade of a high-rise building. In addition to the fact that, according to [22], the value of length of a protective structure should not be less than 1.2 m. However, this parameter was not experimentally confirmed.

Scientific studies into the processes of limiting the spread of fire on the facades of buildings [23] made it possible to reveal the interrelationships of the propagation of fire depending on the parameters of light openings and the presence of inter-floor window partitions on the facade of the building.

Separately, one should note work [24] on the study of the effectiveness of «horizontal protrusions» beyond the external enclosing structure of the building, which in the future received the term fire-proof eaves. According to the results of the field tests, the dependences of changes in the heat flow values at the level of 1 m above the window opening were established. The width of the fire-proof eaves was: 0.0 m; 0.3 m; 0.6 m; and 1 m. The specific heat release from the model simulated fire was 300 kW/m^2. On the basis of field tests, it was determined that for a facade with a fireproof eaves 0.3 m wide, the value of heat flow decreased by an average of 50 %. For a fire-proof eaves with a width of 0.6 m – by 60 %, and for a fire-proof eaves with a width of 1.0 m – by 75 %. The resulting dependences made it possible to evaluate the effectiveness of fire-fighting eaves; along with this, the issue of assessing the relationship between the size of the window interfloor partition and the parameters of the width of the eaves itself remains unresolved.

In work [23], the height of the interfloor partition of 1 m was taken as a basis, which at that time corresponded to architectural trends to one degree or another. Currently, window sizes can vary from the standard 1470×1460 mm to the continuous glass filling of the opening within the floor, namely from the floor to the ceiling (panoramic windows).

Our review of studies into the spread of fire on the surface of facades of buildings showed the lack of a unified approach regarding their structural parameters and fire prevention obstacles that limit the propagation of fire on the surface of the facade. Taking into account the requirements by DBN B.2.2-41:2019 and DBN B.1.1-7:2016, it is appropriate to study the structural parameters of fire barriers as a factor influencing the prevention of fire propagation on the surface of the facade.

3. The aim and objectives of the study

The purpose of our study is to determine the influence of facade parameters and the width of a fire-proof eaves on preventing the spread of fire through the external vertical structures of buildings. Scientific results will make it possible to review the criteria for the effectiveness of limiting the propagation of facade fire with their further integration into the fire protection system of buildings and structures. Our studies could be used by project institutions to improve the regulatory framework in the field of construction fire safety.

To achieve the goal, the following tasks were solved:

– to investigate by using FDS-modeling the relationships between the parameters of external enclosing structures and a fire-proof eaves on the processes of limiting the spread of fire on the example of a real residential building;

– to investigate the influence of minimum parameters of the height of the inter-floor window partition in the absence of a fire protection eaves on the spread of fire;

– to establish the dependence of temperature changes near the surface of the facade, which is above the fire floor, on the width of a fire-proof eaves and the height of a window interfloor partition.

4. The study materials and methods

The object of this study is the process of fire propagation through the surface of external wall structures with facade thermal insulation. The hypothesis of the study assumes that the height of a window interfloor partition and the width of a fire-proof eaves can be interrelated parameters and affect the effectiveness of fire limitation. Thus, there is a task to investigate the relationship between the parameters of external enclosing structures and the fire-proof eaves on the processes of limiting the spread of fire to the higher floor of the building.

Fig. 2 shows a calculation scheme that makes it possible to visualize the process of fire propagation and the basic parameters that affect it.

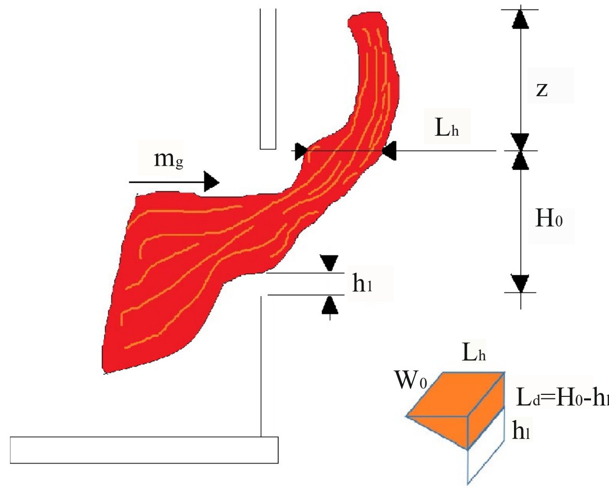


Fig. 2. Visualization of parameters that affect the spread of fire up the facades of buildings

This approach is adapted to determine the value of the heat flow depending on the parameters of a window openings and the fire load inside the room. The resulting dependence takes the form:

$$m_g u=\left(\rho_\infty-\rho_g\right)gV=\left(\rho_\infty-\rho_g\right)g\left(\frac{L_h W_o\left(H_o-h_l\right)}{2}\right), \quad (1)$$

where m_g is the heat flow value; u – average leakage speed, m/s; ρ_∞ – average value of air density, kg/m^3; ρ_g is the average value of gas density, kg/m^3; g – 9.81, m/s^2; V – leakage volume, m^3; L_h is the estimated width of the flame, m; W_o – window width, m; H_o is the height of the window, m; h_1 is the neutral height of the plane, m.

In the case of conducting tests to investigate the effectiveness of ensuring the limitation of the spread of fire when using class B model fires and determining their required area for facades of a certain geometric shape (height and width), the following equation [8] should be used:

$$D=\left(\frac{8W_o m_g^2 T_g^2}{\pi\rho_\infty^2 T_\infty\left(T_g-T_\infty\right)g\left(W_o\left(H_o-h_l\right)\right)^2}\right). \quad (2)$$

These mathematical dependences were verified and tested by full-scale experimental studies to obtain patterns of changes in the distribution of heat flow along external enclosing structures from the window parameters of the room where the fire is simulated. The disadvantage of the studies is the limited data on the parameters of the window itself, namely, its width of 0.94 m and 2.6 m, as well as the height of 1.4 m are taken into account; 2.0 m; 2.7 m. This does not take into account modern architectural trends and the variety of design solutions.

Analyzing the effectiveness of one or another requirement of building regulations requires quite extensive work, and also, as a rule, involves experimental studies and tests, including field tests, which are quite expensive. Modern computer software packages, in particular FDS modeling, allow for the analysis of certain volume-planning and structural solutions using the method of mathematical modeling. Their advantage, in comparison with full-scale tests, is the provision of high convergence of initial conditions and the provision of stable parameters for their conduct (environmental conditions, fire load, parameters and accuracy of metrological equipment, etc.) [25, 26]. Thus, FDS simulation will make it possible to investigate the influence of parameters of the external enclosing structures and the fire-proof eaves on the processes of limiting the spread of fire on the example of a real residential building and to build the corresponding dependence plots.

The temperature value of 250 °C, which corresponds to the destruction temperature of a standard metal-plastic window structure with a glass thickness of 3 mm, was adopted as an assessment criterion for ensuring the conditions for limiting the spread of fire. Temperature control will take place at a distance of 1–2 mm from the surface of the facade in the center of the floor (1.4 m).

The duration of modeling for each investigated variant of the structural execution of the facade will be 15 minutes. This duration is determined by the standard arrival time of fire-rescue units for cities (10 minutes), as well as 5 minutes for the deployment of fire-rescue units and the response of forces and means to extinguish the fire. During fire simulation, for each studied version of the facade construction, the highest temperature value will be determined, which will be recorded at the level of 1.4 m of the facade of the floor, which is higher than the floor where the fire occurs.

During the simulation, the wind effect is not simulated as such, which can create conditions for reducing the density and uniformity of the heat flow and reducing the height of the fire flame. It should also be taken into account that the air flow, which is directed towards the building, will create a support and a zone of increased pressure. At the same time, cold air due to swirling will enter the heating zone of the facade and, accordingly, can cool the wall of the building.

5. Results of investigating the influence of facade parameters and the width of a fire-proof eaves on the spread of fire

5. 1. Studying the processes of limiting the spread of fire on the example of an actual residential building

When planning the experiment, the parameters that affect the fire temperature and are fixed at the level of 1.4 m of the building facade, located above the fire floor, were investigated. These parameters include the value of height of an interfloor window partition (*h*, m) and the width of a fire-resistant eaves of a rectangular shape, which protrudes beyond the building facade (*b*, m). Fig. 3 shows the visualization of the studied parameters.

For each investigated parameter, which affects the processes of fire propagation along the facade of buildings, ranges of limit values were defined, as well as a step for each stage of the calculation. Table 1 gives the intervals of the studied parameters.

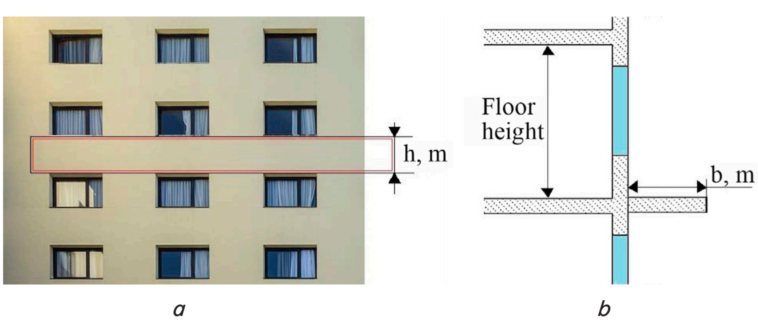


Fig. 3. Visualization of the studied parameters: *a* – interfloor window partition; *b* – visualization of a fire-proof eaves

Table 1

Intervals of parameters in the experiment selected as critical factors

Fire-proof eaves width, m						Height of interfloor window partitions, m				
0.0	0.3	0.4	0.5	0.6	0.75	0.2	0.4	0.6	0.8	1.0
Experiment number						Experiment number				
1	2	3	4	5	6	1	2	3	4	5

Thus, the essence of our experiment is that for each width of a fire-proof eaves, which protrudes beyond the facade of the building, the nature of fire propagation is investigated depending on the height of the interfloor window partitions. Based on the resulting data, a dependence plot is built, taking into account the maximum temperature, which was recorded at the level of 1.4 m of the facade of the building floor, located above the fire floor.

At the first stage of research, a model of the building was constructed on the basis of computational hydrodynamic models of heat and mass transfer, which are included in the FDS software package.

A model of a four-story building was built, the facade of which is made of non-combustible materials. On the first two floors, there are shop and office premises, that is, public premises. There are apartments on the third and fourth floors. The construction material of the building consists of brick with a density of 1900 kg/m^3, a specific heat capacity of 2.2 kJ/(kg·K), and a thermal conductivity of 1.36 W/(m·K). Monolithic concrete structures with a density of 2280 kg/m^3, a specific heat capacity of 2.04 kJ/(kg·K) and a thermal conductivity of 1.35 W/(m·K). The light holes (windows) of the building are open to create the most unfavorable conditions for the spread of fire. The step of the calculation grid of the FDS model is 25 cm^2, which is due to the geometric dimensions of the building model and the multiplicity of the size of the grid cell relative to the geometric parameters of the fire-proof eaves and interfloor window partitions.

According to the simulated fire scenario, it occurs on the 2nd floor in the office premises. In the immediate place of fire, the flame and its dangerous factors spread freely from the windows of the room. At the level of the 2nd and 3rd floors, there are temperature gauges in the gas environment, to obtain plots of the temperature regime in the window area. The facade of the building is absolutely vertical, without protrusions and angles of adjacent facade planes. The surface of the facade wall is set as an animated surface with the possibility of displaying its heating temperature. Fig. 4 shows the FDS model of a building without a fire-proof eaves and the place of installation of meters in a gas environment.

The cause of the fire in the apartment was determined to be ignition of the switchboard with further spread of the fire inside the room, the fire load in the middle of which is 750 kW/m^2 with a maximum combustion temperature of 1230 °C. The flame spreads across the surface of the room at a speed of 0.025 m/s. During calculations, the work of fire extinguishing or smoke removal systems was not taken into account, i.e., the fire evolved freely throughout the duration of the simulation.

At the first stage of modeling, experiment 1–5 was studied, namely, the variant of the height of the interfloor partition of 1 m and the width of the fire-proof eaves of 0.0 m, i.e., without an eaves. The resulting data will be taken as a basis when determining the actual protection of the object from the spread of facade fire. The next stages of research consist in determining the temperature data that was recorded at the level of 1.4 m of the facade of the building floor, located above the fire floor, for all stages of the experiment. The resulting data are entered into a summary table. Fig. 5 shows temperature distributions from the fire according to the results of experiments 1–5.

The resulting data demonstrate that with a height of 1.0 m between floors and the absence of a fire-proof eaves, the critical temperature value of 250 °C, which corresponds to the temperature of destruction of a standard metal-plastic window structure, is reached practically immediately. Thus, the conditions for limiting the spread of fire from one fire-resistant compartment to another are not provided. Fig. 6 shows the plots of temperature regime at the level of the window of the 2nd floor (above the fire) and the window of the 3rd floor located above, while the red line indicates the critical temperature limit.

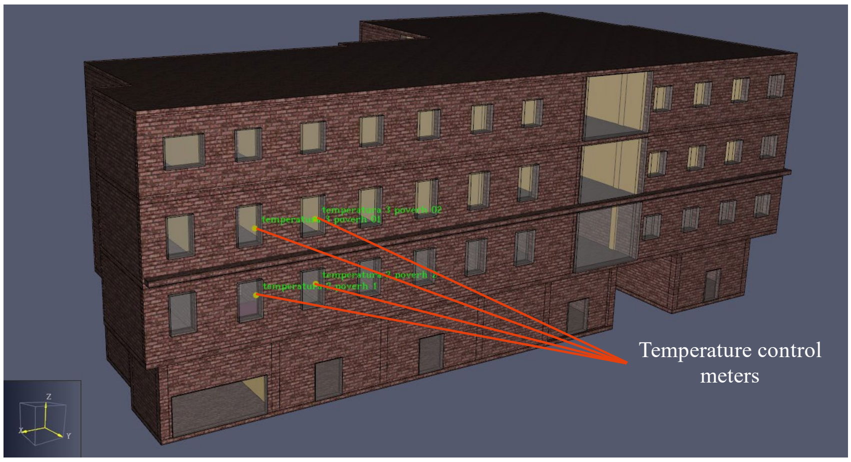


Fig. 4. Model of the building

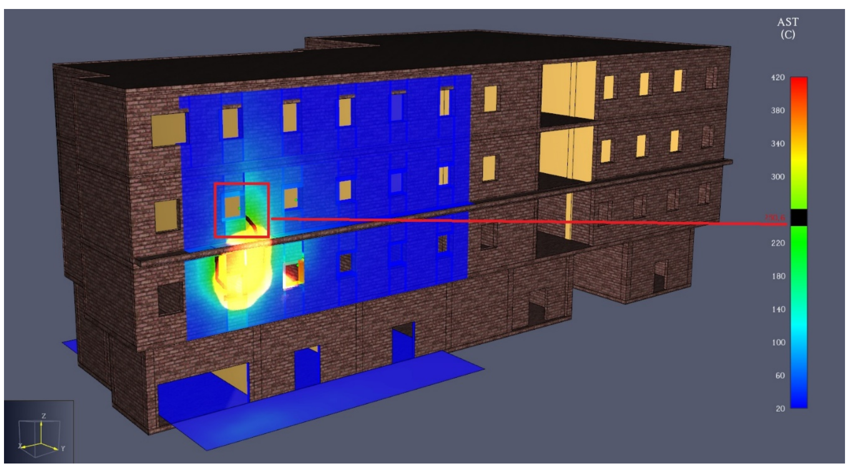
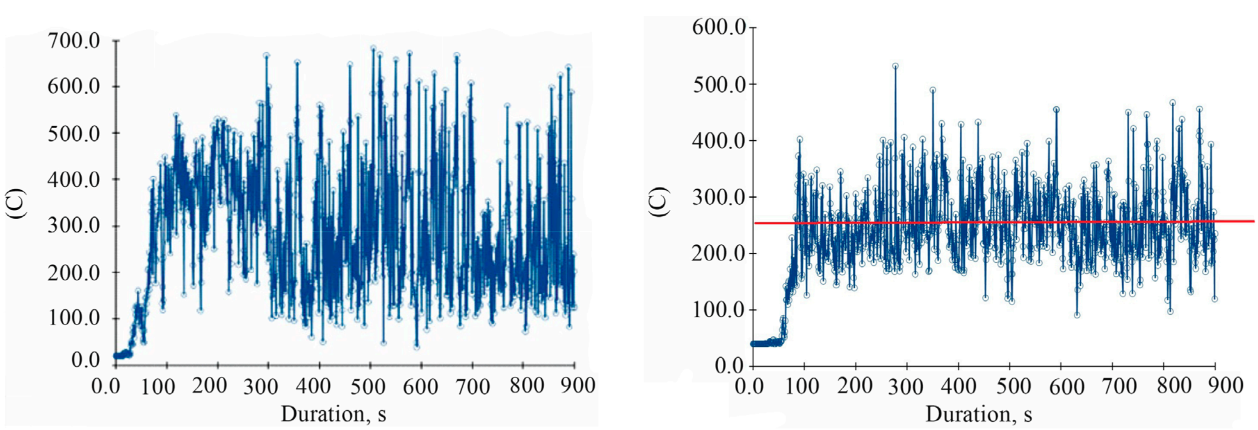


Fig. 5. Results of temperature effects from a fire on the facade of the building according to scenario 1–5



a *b*

Fig. 6. Plots of temperature regime: *a* — at the level of the 2nd floor; *b* — at the level of the 3rd floor

According to the resulting data, it was established that for a building with a window width of 1460 mm, a height of an interfloor window partition of 1.0 m, and the absence of a fire protection eaves, the conditions for the fire not to spread to the higher floor are not met. On the surface of the external enclosing structure of the facade at the level of the floor above, the temperature due to the effect of fire is 435 °C. Thus, the simulation was carried out under the specified conditions for fire-proof eaves with a width of 0.3 m to 0.75 m with a step of increasing the width of the eaves by 0.1 m according to the experimental plan defined in Table 1.

According to the results of our research, the dependences of parameters of the interfloor window partition s and the width of the eaves were established. Namely, for the case when the wall height is 1.0 m and the width of the fire-proof eaves is 0.75 m, the temperature value at the level of 1.4 m of the facade of the building floor, located above the fire floor, is 180 °C. That is, the safety condition of 250 °C is fulfilled. At the same time, the critical width of the fire-proof eaves in the presence of a 1.0 m high interfloor window partition is a width of 0.4 m. Under these conditions, a temperature of up to 245 °C was recorded at a height of 1.4 m on the facade of the building floor located above the fire floor.

Fig. 7 shows the visualization of temperature distributions on the facade of the building. According to the resulting data, a plot (Fig. 8) of the temperature regime for this case of the structural parameters of the facade at the level of 1.4 m of the floor, which is above the fire floor, was constructed.

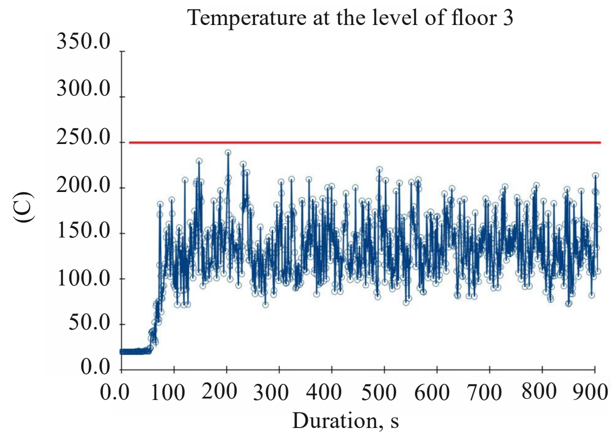


Fig. 8. Plot of temperature regime at the level of 1.4 m of the facade of the building floor, located above the fire floor, with a height of the interfloor window partition of 1.0 m and a width of the fire-proof eaves of 0.4 m

Thus, under the given modeling conditions, the critical temperature of 250 °C on the surface of external wall structures with facade thermal insulation is not reached.

5. 2. Studying the influence of minimum parameters of the height of an interfloor window partition in the absence of a fire-proof eaves

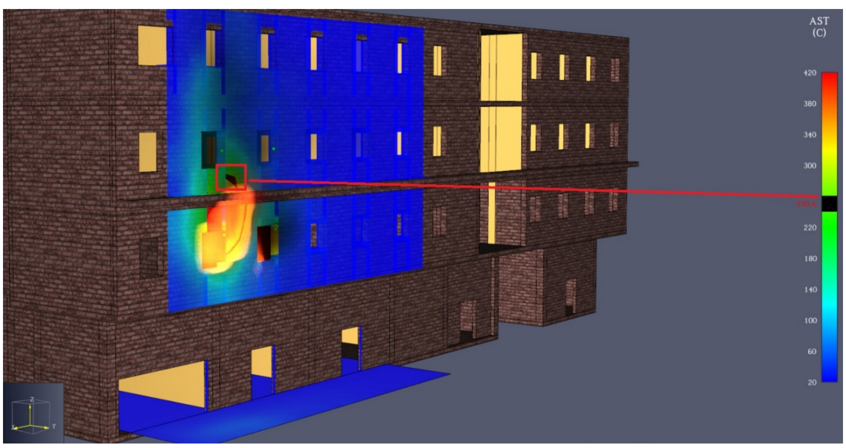


Fig. 7. Visualization of temperature distributions and the spread of fire at a height of an interfloor window partition of 1.0 m and a width of the fire-proof eaves of 0.4 m

The study of minimum parameters of the height of an interfloor window partition (0.2 m) in the absence of a fire protection eaves showed that under these conditions the spread of fire and its dangerous factors is actually not limited in any way.

Thus, the temperature value at the level of 1.4 m of the facade of the building floor, located above the fire floor, was 480 °C.

Fig. 9 shows the visualization of temperature distributions and fire propagation.

Fig. 10 demonstrates a plot of the temperature regime for the examined part of the facade, while the red line indicates the limit of the critical temperature.

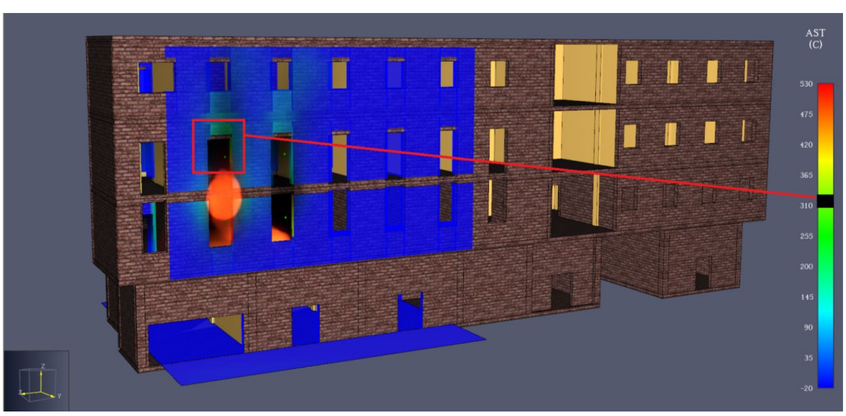


Fig. 9. Visualization of temperature distributions and the spread of fire at a height of the interfloor window partition of 0.2 m and a width of the fire-proof eaves of 0.0 m

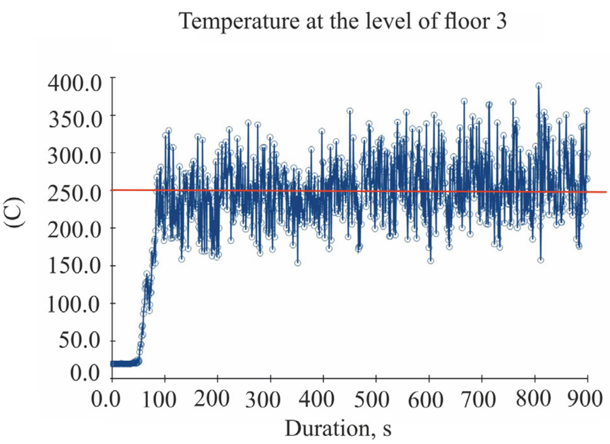


Fig. 10. Plot of temperature regime at the level of 1.4 m of the facade of the building floor, located above the fire floor, with a height of the interfloor window partition of 0.2 m and a width of the fire-proof eaves of 0.0 m

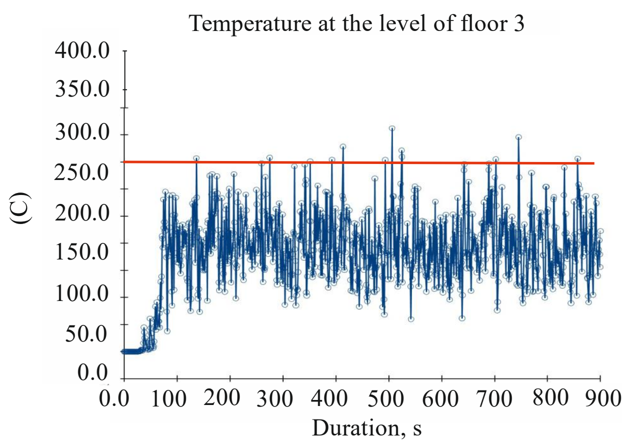


Fig. 12. Plot of temperature regime at the level of 1.4 m of the facade of the building floor, located above the fire floor, with a height of the interfloor window partition of 0.6 m and a width of the fire-proof eaves of 0.5 m

Based on the resulting data, a plot (Fig. 10) of the temperature regime for this case of the structural parameters of the facade at the level of 1.4 m of the floor, which is above the fire floor, was constructed. The resulting data show an excess of the critical temperature, namely reaching 480 °C on the surface of the external wall structures with facade thermal insulation.

5. 3. Studying the dependence of temperature change on the width of a fire protection eaves and the height of an interfloor partition

In order to study the influence of height of the interfloor window partition, simulations were performed under similar initial fire conditions. According to the experiment plan, the sizes of fire-proof eaves with a width of 0.3 m to 0.75 m and a wall from 0.2 m to 1.0 m with a step of increasing the height by 0.2 m were adopted.

According to the results of this stage of research, the limit conditions of the width of the fire-proof eaves and the height of the window interfloor partitions, under which the safety condition is met, were revealed. For these modeling conditions, the critical value of width of the fire-proof eaves was 0.5 m and the height of the interfloor window partition was 0.6 m.

Results from this modeling stage are shown in Fig. 11, 12.

Thus, according to the results of this modeling stage, the dependence of the safety criterion on not exceeding the critical temperature of 250 °C at the level of 1.4 m of the building facade above the fire floor was revealed. It is achieved when the width of the fire-proof eaves is at least 0.4 m and the height of a window interfloor partition is 1.0 m, as well as the width of the fire-proof eaves is 0.5 m, and the height of the window wall is 0.6 m. This allows us to conclude that the height of the window interfloor partition has less influence than the width of the fire-proof eaves that separates the floor where the fire occurs and the floors that are located above.

Table 2 gives summary data on the maximum temperature value near the surface of the facade, depending on the width of a fire-proof eaves and the height of a window interfloor partition. The green color indicates the conditions under which the safety criterion is met, namely that the fire does not spread along the facade to the floor above.

Fig. 13 shows the plots of dependences of changes in temperature near the surface of the facade for each studied width of the fire protection eaves and the height of the window interfloor partition.

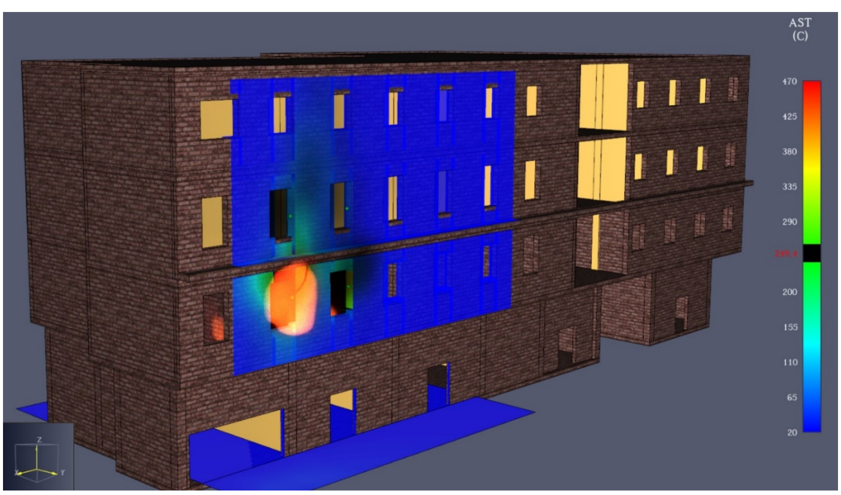


Fig. 11. Visualization of temperature distributions and the spread of fire at a height of the interfloor window partition of 0.6 m and a width of the fire-proof eaves of 0.5 m

Table 2

Value near the surface of the facade at the level of 1.4 m of the building floor, located above the fire floor, depending on the width of a fire-proof eaves and the height of a window interfloor partition

Eaves width, m	Height of interfloor window partition, m				
	0.2	0.4	0.6	0.8	1.0
0.0	480	460	445	440	435
0.3	410	400	360	350	330
0.4	400	380	290	270	245
0.5	340	320	245	240	230
0.6	315	290	240	220	210
0.75	305	275	230	190	180

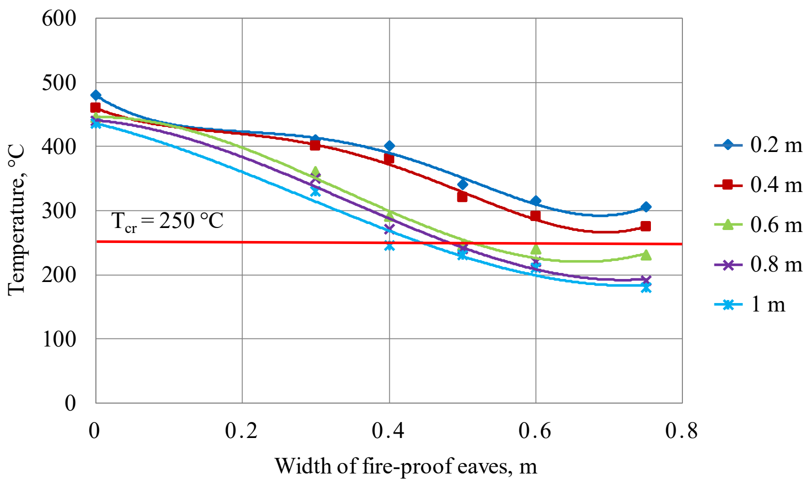


Fig. 13. Dependence plot of changes in temperature values depending on the width of a fire-proof eaves and the height of a window interfloor partition

Experimental data on the change in temperature values are fitted to polynomial dependences y with the corresponding coefficients of determination R^2 at different heights of a window interfloor partition:

– 0.2 m: $y=5956x^4-8610.4x^3+3790.3x^2-744.42x+479.9$; $R^2=0.9883$;

– 0.4 m: $y=4550.6x^4-6116.5x^3+2306.2x^2-454.78x+459.92$; $R^2=0.9934$;

– 0.6 m: $y=1590.2x^3-1592.2x^2+16.487x+445.85$; $R^2=0.9866$;

– 0.8 m: $y=780.05x^3-663.08x^2-278.39x+436.18$; $R^2=0.9787$;

– 1 m: $y=1150.6x^3-1171.7x^2-98.769x+441.01$; $R^2=0.9855$.

In this way, it was established that the critical width of a fire-proof eaves in the presence of a 1.0 m high interfloor window partition is a width of 0.4 m. Under these conditions, at a height of 1.4 m of the facade of the building floor located above the fire floor, a temperature of up to 245 °C was recorded.

6. Discussion of results of investigating the influence of parameters of the facade and a fire protection eaves on the spread of fire

The resulting data, shown by plots in Fig. 13, demonstrate that with an increase in the width of a fire-proof eaves and an increase in the height of a window interfloor partition, a polynomial dependence of the decrease in the temperature value is observed. This can be explained by the fact that the height of the window interfloor partition and the width of the fire-proof eaves are interrelated parameters that affect the spread of fire through the external vertical structures of buildings. In contrast to the data reported in [21, 24], we have demonstrated that increasing the effectiveness of fire-proof eaves can be achieved not only by increasing their width. This effect can be achieved through other parameters of external walls, namely the height of a window interfloor partition.

In addition, the plots in Fig. 13 and the temperature data in Table 2 demonstrate the possibility of combined application of the parameters of the width of the fire-proof eaves and the height of the window interfloor partition. This makes it possible to determine the most effective planning solutions, which ensure the limitation of the spread of fire to the upper floor along the facade of the building with different parameters of fire-resistant eaves and window interfloor partitions. It was determined that these conditions are met with a wall height of 1.0 m and a fire-resistant eaves width of 0.75 m. At the same time, the temperature value at the level of 1.4 m of the facade of the building floor, located above the fire floor, is 180 °C. That is, the safety condition of 250 °C is met (Table 2).

It should be noted that these dependences hold for external wall structures with facade thermal insulation and equipped with thick-layer plaster (class A facade systems) according to DBN V.2.6-33:2018 «External wall structures with facade thermal insulation». In the case of using combustible cladding materials in the design of facade systems, the nature of fire propagation and temperature regimes will change taking into account the thermophysical properties of these materials and the intensity of their burning.

As a shortcoming, one should note the lack of data on the influence of the shape of fire-proof eaves on the processes of removing dangerous fire factors from the outer wall of the building.

Studies [16] on computer simulation of aerodynamic flows spreading around a cubic structure on the facade of buildings demonstrate that the straight shapes and sharp edges of the structures cause the emergence of a point of reattachment of the heat flow along the plane of the facade. This phenomenon is negative and requires further research to determine the conditions under which it is possible to reduce its negative effect. The study of indicators of heat flow reduction, obtaining the appropriate efficiency coefficients depending on the shape or type of fireproof eaves may become the subject of further research and affect the provision of fire protection for building facades.

7. Conclusions

1. With the help of computer simulation in the FDS environment, the parameters that affect the processes of fire propagation along the facade of buildings were studied. The dependence of the safety criterion on not exceeding the critical temperature of 250 °C at the level of 1.4 m of the facade of the building floor, which is achieved with specific parameters of the facade and the width of the fire-proof eaves, was revealed.

2. Comparing the results of our studies, it was determined that the height of a window interfloor partition has less influence than the width of a fire-proof eaves. For the range of height of the window interfloor partition between 0.2 m and 1.0 m, the value of the fire temperature can be reduced by up to 35 %. At the same time, for the range of width of the fire-proof eaves from 0.0 m to 0.75 m, the temperature value can be reduced by up to 60 %.

3. It was established that changes in temperature values along the facade of the building, which is above the fire floor, for each investigated width of the fire-proof eaves and depending on the height of the window interfloor partition follow polynomial dependences. The conditions under which the safety criterion is met, namely the fact that the

fire does not spread along the facade to the upper floor, have been identified. The width of a fire-proof eaves must be at least 0.4 m while the height of a window interfloor partition should be 1.0 m, or the width of a fire-proof eaves must be 0.5 m while the height of an interfloor window partition should be 0.6 m.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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