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INFLUENCE OF THE FACADE SLOPE ON FIRE PROPAGATION PROCESSES ON HIGHER FLOORS

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The study considers the issue of the influence of the structural parameters of the facade on the processes of fire propagation through the external enclosing structures of buildings. The object of the study is the process of temperature changes on the surface of the inclined external enclosing structures of the building due to the action of fire.

The study of the influence of the angles of inclination of the facade on the processes of fire propagation and the nature of temperature distributions on the surface of the facade was carried out. During the research, the methodology of experimental tests was used to limit the spread of fire along the facades using an installation that allows you to reproduce the angles of inclination. As the studied fragment of the facade, an external enclosing structure made of non-combustible materials without external cladding was used. Thermocouples were placed on the surface of the facade, which made it possible to obtain temperature data near its surface in real mode throughout the duration of the research.

A class 34B model fire source provided a fire load of at least 2,200 MJ/m^2 and an average temperature of 800–850 °C throughout the duration of the research.

It was found that in the presence of a slope of the facade at an angle of +20°, an increase in temperature near the surface of the studied area by 24–26 % was observed. In the presence of an inclination of the facade at an angle of –20°, a decrease in temperature near the surface of the studied area by up to 55 % was observed.

The obtained dependences will make it possible to review the approaches to the existing field methods of fire hazard assessment of facade systems. The practical result of the implementation of the obtained data may be the introduction of changes to building regulations to increase the level of fire protection of facade systems and buildings in general

Keywords: assessment of the spread of facade fire, patterns of fire spread, inclined facade fires, methods of facade testing

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1. Introduction

Facade fires, especially for high-rise buildings, are one of the most dangerous types of fires. A significant number of fires spread between the floors of the building from the outside along its facade, with subsequent spread into the middle of the premises due to the destruction of external enclosing structures or due to the destruction of the filling of light openings, including windows. An analysis of data on facade fires of buildings in the world from 1960 to 2021 showed that in the 1960s and 1970s, facade fires mostly spread over 10 to 15 floors. For the period of 2000–2020, facade fires spread over 20–30 floors, and for Middle Eastern countries over 60–70 floors [1, 2]. These data can be explained by a significant increase in the number of floors of new buildings over the past 20–30 years and architectural trends in the world.

A survey of the most unusual modern buildings shows that the angles of inclination of the facade plane are within 15–20 degrees. For more common typical designs of buildings of shopping and entertainment centers or office buildings, the angle of inclination of the facade is within 5–8°, as for Europe, the USA, and Asia [3]. Figure1 shows a photograph of buildings that are tilted relative to the vertical.

Thus, during the study of the influence of the slope of the facade on the assessment of the possibility of fire spreading to the higher floors, it was decided to investigate the maximum values of the slopes of the facades of buildings. Namely, slopes of +20° and –20° relative to the vertical were studied, and for comparison, a study was conducted for a vertically located facade. The research data will also allow obtaining data on temperature distributions from fire for facades with different angles of inclination of the plane.

Ensuring the limitation of the spread of fires on the facades of buildings and structures is one of the main requirements of fire safety, which is provided for by the majority of building codes in the world, as well as provided for by the European Technical Regulation 305/2011 [4].

It should be noted separately that in more than 40 % of facade fires in the period from 2000 to 2022, in particular those recorded in high-rise buildings, the facade was made of non-combustible materials in accordance with the requirements of building regulations [5]. That is, the presence of a non-combustible facade is not an absolute guarantee of limiting the spread of fire on building facades but is only one of the factors that can reduce such a probability. This approach is due to the fact that the use of non-combustible facade cladding materials cannot limit the spread of fire to higher floors. This can only be a secondary factor, which will have a greater influence on the speed of the possible spread of the fire to the higher floors.

Fig. 1. Examples of buildings with a slope of the facade plane: *a* – "Falling Skyscraper"; *b* – "Gate of Europe"; *c* – the headquarters building of China Central Television; *d* – "Bella Sky Hotel"

Thus, the question arose of researching the influence of the structural parameters of the facades, namely its angle of inclination, on the processes of assessing the possible spread of fire along the facades of buildings under the same conditions of initial fire development. This will reveal potential ways of improving the existing fire hazard assessment methods of facade systems and external enclosing structures. Also, the obtained data will create prerequisites for improving construction standards to increase the level of fire safety of buildings and structures in general.

Therefore, the relevance of research into this topic is predetermined by the scientific and practical problem of revealing the regularities of the influence of facade slopes on the processes of fire propagation along them, as a theoretical basis for the possibility of preventing facade fires in buildings.

2. Literature review and problem statement

A preliminary analysis of the main existing methods for assessing the spread of fire on the facades of buildings revealed a number of shortcomings that can significantly affect the accuracy of assessing the fire safety of facades. Existing procedures and corresponding test facilities differ both in scale and design. The SP Fire 105 method [6] is actually the single most common and internationally recognized standardized method for evaluating the effectiveness of preventing the spread of fire on the external enclosing structures of a building, as a simulation of a fire inside a building with a broken window. The reason for this is that other methods are more aimed at investigating the fire hazard of facade facing building materials. The LEPIR2 method [7] is considered the most perfect from the point of view of simulating the real parameters of facades. However, this method is the most expensive and can be applied only during the study of facades lined with combustible materials.

In 2002, the UK method BS 8414 [8], for testing the cladding of brick building surfaces, was devised to develop SP Fire 105 [6], which was first published in 2002. Among its features, one should note the use of only a class A fire model hearth, which affects the quality of maintaining the temperature regime. Similar problems are noted in the methodology of Germany, DIN 4102-20 [9]; however, in this methodology one should note a much higher level of applied measuring equipment, which allows evaluation with better accuracy. Work [10] reports the results of comparative studies of the above procedures, which denote that these aspects significantly affect the accuracy of tests of facade systems in relation to fire hazards. At the same time, the applicability of these methods in a number of research works is a subject of discussion, which determines their constant process of improvement

The British standard BS 8414 [8] is taken as the basis for the development of the Australian standard AS 5113:2016 [11]. The disadvantage of this method is the lack of choice of the type of model fire, which significantly affects the conditions of the temperature regime of the tests. In China, the method GB/T 29416-2012 [12] is used, but its procedure does not provide criteria for evaluating the spread of fire to a higher floor.

The issue of reproducing the real parameters of building facades is partially solved in the CAN/ULC S-134 [13] and French LEPIR2 [7] methods, but these methods do not take into account the issue of reproducing the slope of the facade. When devising the methodology in the USA [14], the developer managed to solve the issue of a stable temperature regime by using gas burners. However, among the ways to improve this method, the issue of substantiating the design parameters of the test bench for different types of facade systems should be noted.

To create a temperature regime, model fires of classes A and B, as well as gas burners, are used. The average value of the fire load, as a rule, is in the range of 700–2500 MJ/m^2, and the total duration of the tests is 20–30 minutes [15].

It should be noted that the methods in [6, 7] basically included a study of the assessment of the limitation of the spread of fire along the facade of the building. Standards [8, 9, 11–14] adapted their methods for the study of fire safety of facade thermal insulation, fire resistance of insulation systems of external walls, and the spread of fire inside the studied sample of the facade system. That is, the given methods mostly related to the fire safety of facing materials and their mounting methods.

The preliminary analysis carried out in [16] showed that the existing procedures take limited account of the contact angles of the adjacent plane, the presence of which significantly affects the test results due to the heat flow shielding effect. However, study [17] does not take into account such design parameters of the facade as the size of window openings and the angles of inclination of the facade. Studies [17] are consider the assessment of the spread of fire on inclined surfaces but they concern only the design of roofs and changes in the speed of flame propagation.

Work [18] reports the study into the influence of the inclination of the facade on the processes of fire propagation by conducting mathematical modelin; however, the data do not contain verification of the obtained dependences, in particular, by conducting full-scale fire tests. Work [19] reveals the problems of assessing the resistance of prefabricated facade thermal insulation systems to the spread of fire, as well as aspects of assessing the fire hazard of facing materials used in facade systems. However, in [20], the issue of evaluating the structural parameters of facade systems for the processes of fire propagation through external enclosing structures to the floors above has not been resolved. Paper [20] describes a study into the influence of wind on the processes of evaluating the spread of fire along the facade, which proves the significant influence of external factors on the accuracy of the data obtained from the test results. However, the results are related to the influence of external factors that can affect the assessment processes.

Research [21] on the influence of the fire load on fire propagation processes made it possible to investigate the change in the nature of fire propagation; however, these research data are more relevant for facades with combustible cladding materials.

In work [22], the factors and regularities that affect the process of assessing the spread of fire to higher floors are investigated. However, this work largely considers the dynamics of fire propagation, and its results are based on computer simulations and do not include field tests.

Thus, an unsolved part of the task to assess the spread of fire along the facades of buildings is the lack of data on the influence of the angle of inclination of the facade on the processes of fire spread along them. This issue is a prerequisite for reviewing existing criteria and analyzing existing procedures of experimental research.

3. The aim and objectives of the study

The purpose of this work is to identify the influence of the inclination of the facade system on the processes of fire propagation through it to the floors located above. This will make it possible to more accurately assess the fire hazard for external enclosing structures for buildings with inclined facades.

To achieve the goal, the following tasks were solved:

– adapting the methodology of experimental studies to assess the limitation of the impact of fire on the facade of the building and providing scientific and methodological support for the studies;

– conducting fire experimental studies for a predefined fire scenario at different angles of inclination of the facade plane;

– checking the convergence of each series of experiments for a certain angle of inclination of the facade fragment.

4. The study materials and methods

The object of research is the processes of fire propagation along the facades of buildings made of non-combustible materials, which can be located at certain angles of inclination relative to the ground.

The hypothesis of the study assumes that under the same initial fire conditions, the slope of the facade can significantly influence the final results of the fire safety assessment of facades.

The methods of generalization of previously performed studies were used to substantiate the requirements for a test installation for assessing the spread of fire on the facades of buildings. Methods of search natural experiment. Polygon fire test methods (according to existing procedures) were also used to study heat exchange processes between the fire source and objects exposed to fire. In order to check the convergence of the series of experiments, variances of the deviations from the average values of the corresponding thermocouples, which were compared by the Fisher method, were calculated.

A new approach undelies he methodology of experimental research, which is based on the reproduction of the actual structural parameters of the facade fragment. Existing approaches could only ensure the adaptation of facade systems and building materials for their facing to existing standardized benches, installations, and fragments of buildings for simulation tests.

The installation for predicting the spread of fire on the facades of buildings is a steel prefabricated frame structure that makes it possible to arrange a fragment of the external non-load-bearing enclosing structure of the floor of the building made of non-combustible materials, with a total height of 2000 mm and a width of 2300 mm, including the adjacent corner plane. To reproduce the fragment of the facade structure under investigation, gas blocks of the D400 brand were adopted as the main material of the external vertical enclosing structure, where the numerical value corresponds to the value of the density of the product, namely 400 kg/m^3. The coefficient of thermal conductivity of gas blocks is 0.11–0.13 W/(m·K) in the dry state, thermal conductivity is in the range of 0.1–0.4 W/(m·K).

In order to know the temperature indicators, thermocouples are placed on each investigated zone of the facade, which are connected to the “Thermokont” information and measurement system.

The window of the fire chamber with the geometric dimensions of 800×1350×1800 mm (height, depth, width) will ensure the free spread of the flame across the entire width of the examined facade fragment.

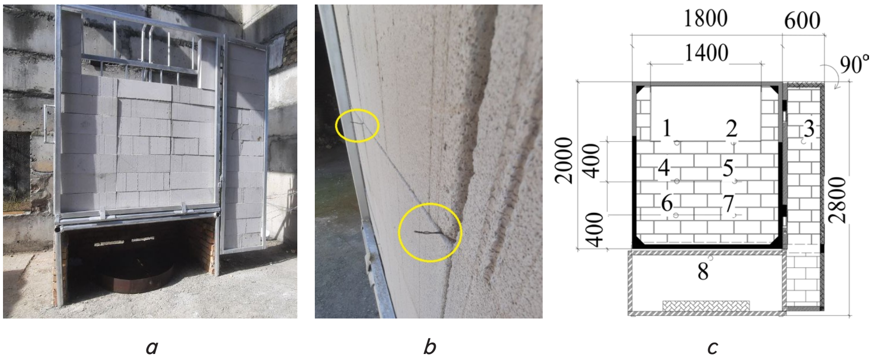
Taking into account the above, the design of the installation should provide the opportunity to study the changes in the dependence of thermal distributions on the facade depending on the angle of inclination of the facade.

5. Results of research on the spread of fire along the faзade of buildings

5. 1. Adaptation of the methodology for studying the influence of faзade slope on the assessment of fire spread

During the research, a device was used to detect patterns of temperature changes on the outer surface of vertical building structures.

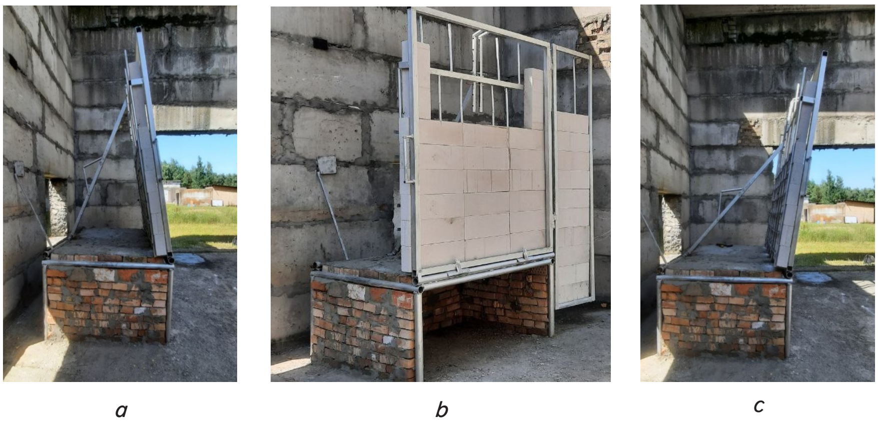
The essence of the research method is to expose the investigated fragment of the facade system to fire for 30 minutes, which is reproduced in the middle of the fire chamber simulating the top of the building. The temperature regime in the middle of the fire chamber must correspond to the standard temperature regime according to the ISO 834-1:1999 standard, or it can be higher. To control the temperature, thermocouples are placed on the surface of the test fragment of the facade structure based on the calculation of 1 thermocouple per 50 cm^2 of the area of the external enclosing structure. Placed thermocouples in the structure of the facade fragment allow obtaining data on temperature distributions near the surface of the facade and, accordingly, provide an opportunity to assess the nature of the spread of fire along the facade. The photograph of the installation is shown in Fig. 2.



a *b* *c*

Fig. 2. General view of the installation: *a* – photograph of the installation; *b* – thermocouples for registering the temperature near the surface of the facade; *c* – diagram of placement of thermocouples (1–8) and overall dimensions of the bench

As a model fire, according to the research methodology, a model fire of class 34B was used, which was filled with Castrol Optigear Synthetic X320/X320 WTO lubricant, in the amount of 60 liters (±200 ml). The presence of this volume of liquid fuel ensured the duration of its burning for at least 30 minutes. The study involves conducting four fire tests for each angle of inclination of the facade system, namely at an angle of –20°, 0°, and +20° relative to the vertical, during which the obtained temperature dependences are recorded. The result of determining the index of the main temperature curve is taken as the arithmetic mean of four test results for each studied slope angle. Fig. 3 shows a photograph of the above installation with the placement of the examined fragment of the facade system at an angle of –20°, 0°, and +20° relative to the vertical.



a *b* *c*

Fig. 3. Investigated options for the placement of the facade: *a* – installing the examined fragment of the facade at an angle of –20° relative to the vertical; *b* – installing the examined fragment of the facade at an angle of 0° relative to the vertical; *c* – installing the examined fragment of the facade at an angle of +20° relative to the vertical

The design of the installation mechanism has been improved to ensure a change in the angle of inclination of the frame relative to the vertical, namely from 70° to 110° and to ensure the possibility of their fixation in the required position. The principle of operation of the mechanism involves the creation of one clamped linear moving in a single plane and a beam kept in balance by means of fixing rods. In the design of the main frame, a distribution plate is arranged, which has holes for fixing the beam in positions corresponding to the angle of inclination of the frame of 70°; 80°; 90°; 100°; and 110°. The implementation of this modification of the installation has made it possible to realize the adaptation of the methodology for the study of the influence of the slope of the facade on the assessment of the spread of fire.

For the possibility of recording temperature distributions on the surface of the investigated fragment of the facade system, a thermal imager is installed at a distance of 5 m from the plane of the facade. During the experimental studies, the installation was located in an enclosing fire box, which made it impossible to be affected by wind loads. The temperature of the surrounding environment was in the range of 22–25 °C, the air humidity was 35–40 %.

The criterion for the spread of fire to the floor above, in particular to the middle of its premises, is the temperature of the destruction of the structure of the transparent element (window). It is accepted that for buildings in the construction of external enclosing structures, which have inter-floor window sills, which are made of non-combustible materials, the destruction of the transparent element occurs at a temperature above 250 °C. This temperature effect should be observed for at least 12 minutes. This criterion is determined by the results of research into the destruction of ordinary window structures under the influence of fire [23].

5. 2. Results of experimental fire studies

According to the results of the conducted full-scale fire studies, a monotonous increase in temperature was observed on the surface of the experimental samples of the facade system placed under the investigated slopes, which can be equated to an exponential distribution. A fragment of the facade system made of non-combustible materials was charred but no ignition of the materials or loss of their integrity occurred for each series of studies. Complete burnout of the fire load in the deck was observed at 30–31 minutes of experimental research. Fig. 4 shows photographs of fire tests for each series of facade placement.

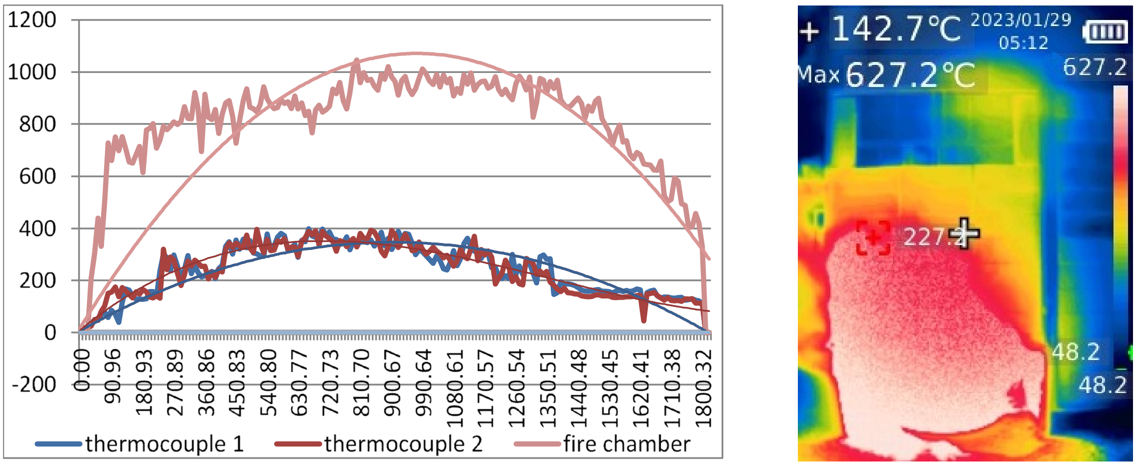
Based on result of each series of fire tests, plots of these temperature regimes were constructed, based on average values as a result of four tests for each investigated case of inclination. The plot shows the change in temperature over time for the area where the window opening is located, namely at a distance of 1400 mm from the upper edge of the fire chamber. In addition, the plots show the curve of the temperature regime in the fire chamber. Fig. 5–7 show plots of the temperature regime for the investigated zone of the facade at different angles of inclination; we also recorded the nature of temperature distributions with a thermal imager at the moment of the maximum temperature regime.

The range of maximum temperature values was determined on the basis of constructed plots of temperature dependences at the relevant investigated points of the facade samples on the duration of thermal exposure of the model fire. Also, with the help of a thermal imager, a visualization of the nature of temperature distributions on the surface of the facade was obtained depending on the angle of its inclination.

The first data were obtained for thermocouples located at the level of the window opening in the fragment of the facade placed at an angle of 0° relative to the vertical (i.e. vertically). For this case, the temperature value according to the polynomial curves at the moment of the peak values of the temperature regime in the fire chamber (from 8 to 25 minutes) is in the range of 350–390 °C. At the same time, for the same thermocouples that are located in the fragment of the facade placed at an angle of +20° relative to the vertical, the temperature value according to the polynomial curves at the moment of the peak values of the temperature regime in the fire chamber is within 440–480 °C. For the fragment of the facade placed at an angle of –20° relative to the vertical, the temperature value for thermocouples T1–T3 according to the polynomial curves at the time of the peak values of the temperature regime in the fire chamber is within 160–180 °C.

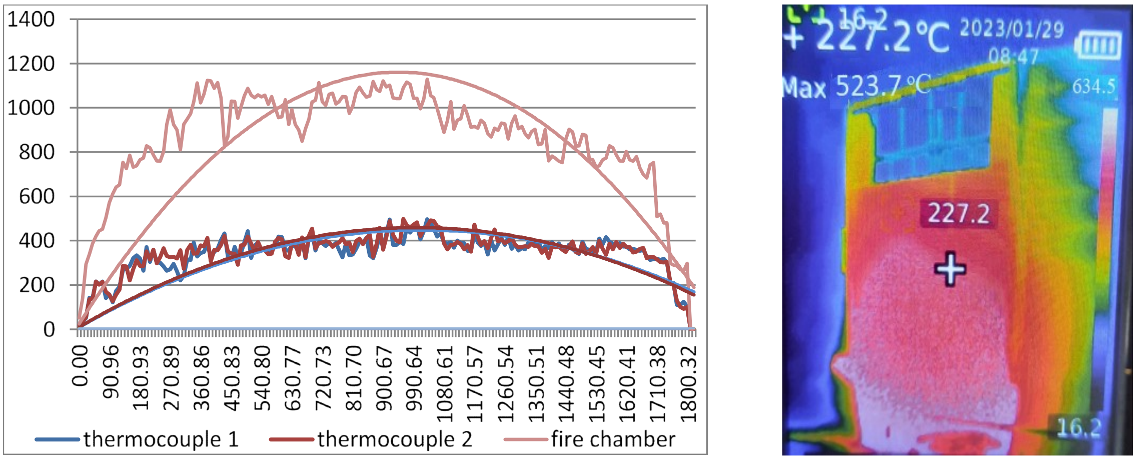

a *b* *c*

Fig. 4. Photograph of live fire studies of the spread of fire on facades that are placed at an angle: *a* — installing the examined fragment of the facade at an angle of 0° relative to the vertical; *b* — installing the examined fragment of the facade at an angle of +20° relative to the vertical; *c* — installing the examined fragment of the facade at an angle of —20° relative to the vertical



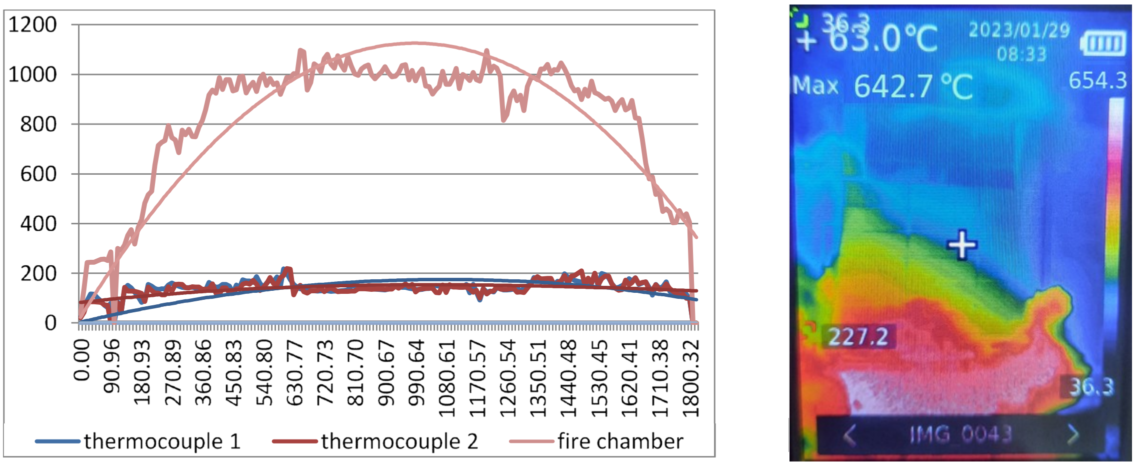
a *b*

Fig. 5. Results of the temperature regime in the area of the window opening at the vertical location of the facade at 0°: *a* — temperature plot; *b* — temperature distributions on the surface of the facade



a *b*

Fig. 6. Results of the temperature regime in the area of the window opening with the vertical location of the facade +20° relative to the vertical: *a* — temperature plot; *b* — the nature of temperature distributions on the surface of the facade



a *b*

Fig. 7. Results of the temperature regime in the area of the window opening with the vertical location of the facade – 20° relative to the vertical: *a* – temperature plot; *b* – the nature of temperature distributions on the surface of the facade

5. 3. Checking the convergence of experiments

In order to check the convergence of the experiment, variances of the deviations from the average values of the corresponding thermocouples, which were compared according to (1), were calculated:

$$d=\frac{\sum_{i=1}^{n}\left(X-\bar{X}\right)^{2}}{n}, \qquad (1)$$

where X is the value of the i-th study;

$\bar{X}$ – average value;

n is the number of studies.

To estimate the variances, we put forward a null hypothesis, that is, it is assumed that the difference between the variances of the research results is zero and the data obtained during the research are samples from the general population.

At the same time, we calculate the Fisher coefficient [24] according to (2):

$$\frac{S_1^2}{S_2^2}=F, \qquad (2)$$

where S_1^2, S_2^2 is the mean square deviation for the sample with the largest and the smallest values obtained during research.

The calculated value of the coefficient F is compared with the tabular value [24]. For this, the level of statistical significance q % (usually it is 5 %) is set, and for the number of degrees of freedom $k_1=n_1-1$ and $k_2=n_2-1$, the tabular value $F_{q,k1,k2}$ is determined, which for a sample of four experimental studies is, for 5 % limits – 6.39, for 1 % of limits – 15.98.

If the inequality $F \le F_{q,k1,k2}$ is satisfied, then for the available data it can be assumed that with statistical reliability $P=1-\frac{q}{100}$, the data do not deny the null hypothesis, that is, the discrepancy between the variances of research results can be considered insignificant and can be explained by the influence of random factors and a limited amount of data. Thus, the data obtained during research are samples from one general population.

If $F \le F_{q,k1,k2}$, based on the obtained results, the null hypothesis is rejected and the discrepancy between the variances of the research results is considered significant, i.e., such data do not belong to the same general population. Thus, on the basis of the given criteria, the analysis and evaluation of variances were carried out for each series of fire studies.

The results of the study of the dispersion of deviations according to the average values of the corresponding thermocouples for the first stage of research are shown in Fig. 8.

The root-mean-square deviations for this series of studies were 20.6 °C, which in terms of relative deviations is 7.6 %, which indicates that the data of each experimental study are as close as possible to the averaged data of the experiment.

The results of the study of the dispersion of deviations according to the average values of the corresponding thermocouples for the second stage of research are shown in Fig. 9.

Thus, the root mean square deviations for this series of studies amounted to 14.8 °C, which in relative deviations is 5.8 %, which indicates that the data of each experimental study are as close as possible to the averaged data of the experiment.

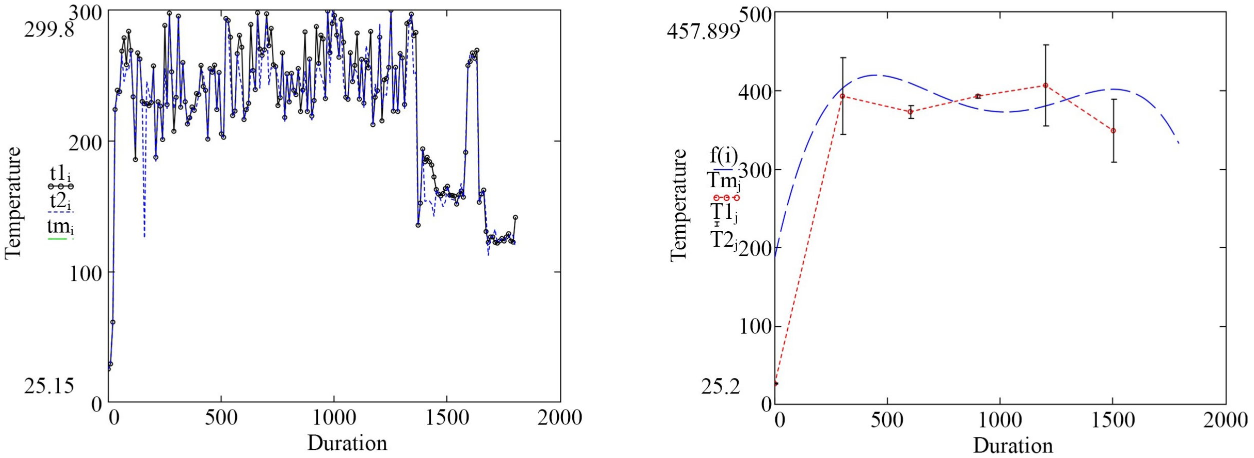
The results of the study of the dispersion of deviations according to the average values of the corresponding thermocouples according to the third stage of research are shown in Fig. 10.

Table 1 gives the generalized adequacy data for thermocouples placed in the area of the lower edge of the window, which is located above the fire chamber, which simulates fire floors for each of the test series during the study of the patterns of fire propagation along external enclosing structures depending on their design parameters.

Table 1

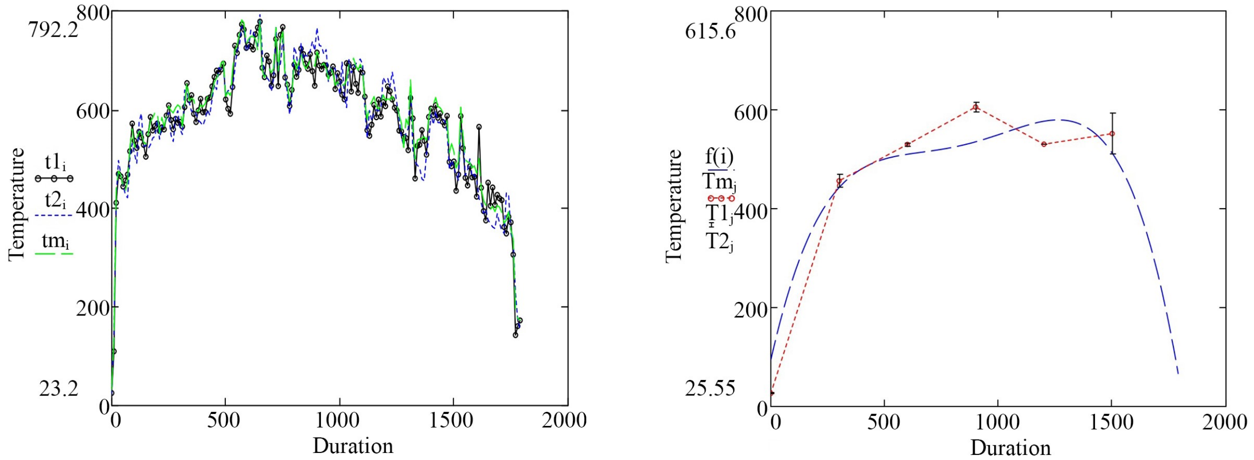
Summarized results of checking the adequacy of the studies carried out to identify the patterns of fire spread in the external enclosing structures

Test series number	Absolute deviation, °C	Relative deviation, %	Standard deviation, °C	Fisher's criterion 5 % – 6.39
Test series 1	15.4	6.6	20.6	1.37
Test series 2	7.9	2.9	8.9	1.21
Test series 3	9.4	7.4	12.0	1.45
Deviation range	7.9÷15.4	2.9÷7.4	8.9÷20.6	1.21÷1.45
Average values	10.9	5.3	13.8	1.35



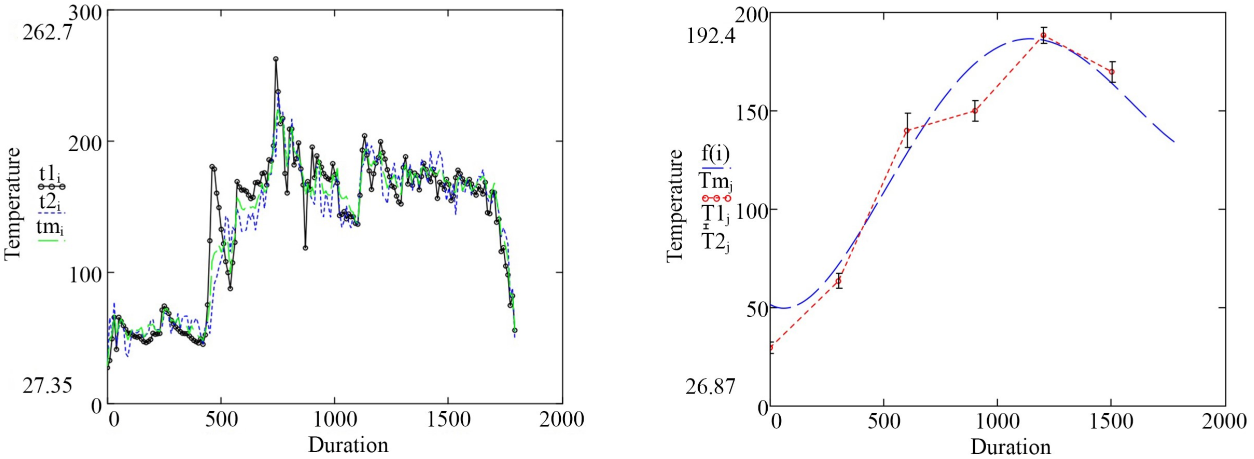
a *b*

Fig. 8. Results of the study of the dispersion of deviations of a series of studies for a vertically placed facade: *a* — a plot of temperature curves; *b* — variances of deviations for thermocouples at the level of the window opening



a *b*

Fig. 9. Results of the study of the dispersion of deviations of a series of studies for the facade placed at an angle of +20° relative to the vertical: *a* — a plot of temperature curves; *b* — variances of deviations for thermocouples



a *b*

Fig. 10. Results of the study of the dispersion of deviations of a series of studies for the facade placed at an angle of −20° relative to the vertical: *a* — a plot of temperature curves; *b* — variances of deviations for thermocouples

Thus, the root mean square deviations for this series of studies amounted to 10.9 °C, which in relative deviations is 5.3 %, which indicates that the data of each experimental study are as close as possible to the averaged data of the experiment. Since the estimated value of Fisher's criterion is less than the tabular value, it can be stated with a statistical probability of 0.95 that the obtained temperature data do not deny the null hypothesis, and their discrepancy can be considered not significant. Thus, the data obtained from the results of an experimental study are samples from one general population, which confirms the general convergence of each individual experiment.

6. Discussion of results of incestigating the impact of the faзade slope on the assessment of the possibility of fire spreading to the higher floors

The results of our research showed a significant influence of the slope of the facade plane on the temperature range in the area of the lower edge of the window above the floor.

Analysis of plots of the temperature regime, which are shown in Fig. 5, revealed the value of the temperature regime in the area of the window opening, namely at a distance of 1400 mm from the upper edge of the fire chamber for the facade which is placed at an angle of 0° relative to the vertical (i.e. absolutely vertical). For this case, the temperature value according to the polynomial curves at the time of the peak values of the temperature regime in the fire chamber (from 500 to 1500 seconds) is in the range of 350–390 °C. This temperature effect was observed during 1300–1500 seconds of the total 30 minutes of research. Thus, taking into account the criterion for the destruction of a transparent element, namely, a temperature of more than 250 °C during a 12-minute exposure (720 seconds), there is a high probability of the destruction of the structure filling the light slot. This can, accordingly, lead to the spread of fire in the middle of the room above the floor. Thus, the assessment result is negative and the conditions for limiting the spread of fire are not met.

Thus, it is possible to make a preliminary conclusion that for an ordinary house with a vertical arrangement of the facade and with the maximum height of the inter-floor window wall, there is a high probability of the spread of a facade fire. The free spread of fire from an open window creates a critical temperature regime in the range of 350–390 °C at the level of the window located above, which will accordingly cause its destruction and the spread of fire in the middle of the upper floor.

The results of the second stage of research, namely the fire tests of the examined fragment of the facade installed at an angle of +20°, showed that the maximum temperature range for the window slot area was 440–480 °C. This temperature effect was observed during 1300–1500 seconds of the total 30 minutes of research. Taking into account the criterion of the destruction of the transparent element, there is a high probability of the destruction of the structure filling the light opening and, accordingly, the spread of fire into the middle of the room above the floor.

Separately, it should be noted that the presence of a facade slope at an angle of +20° affects the temperature increase near the surface of the studied area by 24–26 %. At the same time, the flame contact area with the facade increases by up to 40 % for this type of structure of the facade fragment. These conditions for the construction of the facade are much more dangerous compared to a vertically located facade and can potentially cause a much faster development of a facade fire.

The results of the third stage of research, namely the fire tests of the examined fragment of the facade, installed at an angle of –20°, showed that the maximum temperature range for the area of the window opening was 160–180 °C. This temperature effect was observed during 1200–1300 seconds of the total 30 minutes of research. It should be noted that, under these conditions, the probability of destruction of the structure filling the light slot is significantly reduced compared to the previous series of tests. This means that the conditions for limiting the spread of flame in the middle of the room are fulfilled and the test has a positive conclusion.

The presence of a facade slope at an angle of –20° affects the decrease in temperature near the surface of the studied area by 50–55 %, and the area of flame contact with the facade decreases by 70 % for this type of structure of the facade fragment. Thus, these conditions for the structural execution of the facade are safer both in comparison with an inclined facade at an angle of +20° and with a vertical facade. That is, under the same conditions of fire development, the size of the window from which the flame spreads, as well as the height of the inter-floor window sill, this type of structural execution of the facade is the safest.

Our findings demonstrate that the accuracy of the assessment and their results, even according to one procedure, can differ significantly when taking into account the real parameters of the facades. Research [15] substantiated the need to find a unified approach to assessing the fire hazard of facades. At the same time, the solution to the issue of comprehensive assessment of the fire hazard of facades can consist in summarizing only the most relevant evaluation criteria. At the same time, the scenarios of the initial development of the fire can also be different and are formed based on the result of the analysis of potential risks for a particular building.

It should be noted that the research data is limited by the scale of the test facility. However, this question to a greater extent concerns the accuracy of the obtained data and the rationality of the organization of the experiment. In addition, for each type of structure of the facade of the house, the materials used to equip the facade systems and the size of the window opening, the results of the temperature regimes near the surface of the facade will probably differ.

Among the shortcomings of these studies, it is appropriate to note the lack of a real window structure on the floor, which is located above the fire floor. An additional analysis of deformation and destruction of the window would make it possible to draw a more accurate conclusion about the possibility of the facade fire spreading to the middle of the upper floor. In addition, these studies do not take into account the possibility of external influence of wind and the range of ambient temperature.

The promising development of these studies may consist in taking into account the listed shortcomings, as well as studying the influence of facade fire barriers (fire eaves, drencher systems, etc.) on the processes of limiting the spread of fire. The data could become the basis for changing approaches to the evaluation of fire propagation processes along external vertical enclosing structures and increase the accuracy of the evaluation of fire propagation processes along building facades.

7. Conclusions

1. The need to study a previously unresearched structural parameter of the building facade, which can affect the evaluation of facade fire propagation processes, has been substantiated. It was found that the existing procedures of testing facades for fire hazard indicators do not take into account such a structural parameter as the slope of the facade.

It was determined that for existing buildings with a sloping facade, the most common range of angles of inclination of its plane is 15–20 degrees.

Adaptation of the methodology of experimental studies for assessing the limitation of the effect of fire on the facade of the building from the source of thermal radiation was carried out. Work was performed to provide the test facility for assessing the spread of fire on the facades of buildings with the necessary transformation characteristics and measuring equipment for the analysis of the received data.

2. The results of our experiments showed that under the same temperature conditions, the nature of the temperature regime near the surface of the investigated facade has significant differences for each series of tests. With the same conditions of the initial development of the fire and the criteria for assessing its spread to the upper floor, it was found that the change in the angle of the facade can significantly affect the final conclusion when assessing the possibility of fire spread using this procedure.

It was determined that for the facade, which is placed vertically, the average temperature values near the surface of the studied area were within 350–390 °C at the moment of the maximum temperature regime in the fire chamber. In the presence of a slope of the facade at an angle of +20°, an increase in temperature near the surface of the studied area was actually observed by 24–26 %. At the same time, the flame contact area with the facade increases to 40 % for this type of structure of the facade fragment. The presence of a slope of the facade at an angle of –20° affected the decrease of the temperature near the surface of the studied zone by 50–55 %, and the area of contact of the flame with the facade decreased by 70 %.

Thus, the expediency of revising the methodology for assessing the possibility of the spread of facade fires has been substantiated. The new method should take into account not only the finishing materials but also the structural characteristics of the facade under study, namely: its inclination angles, adjacent plane angles, the real distance between the light openings, and the area of their openings.

3. The study of variances of deviations from the average values of the corresponding thermocouples showed that the root mean square deviations for each series of experimental studies are within 5.8–7.6 %. The results show that the data of each experimental study are as close as possible to the averaged data of the experiment, and the variances belong to one general set of results.

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.

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