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Fireproof suspended ceilings with high fire resistance limits

Огнезащитные подвесные потолки с высокими пределами огнестойкости

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Key words: oil and gas complex; building structure; steel construction; fire resistance; hydrocarbon fire; standard fire; suspended ceiling

Ключевые слова: нефтегазовый комплекс; строительная конструкция; стальная конструкция; огнестойкость; углеводородный пожар; стандартный пожар; подвесной потолок

Abstract. Suspended ceiling is an effective way to fire protection of horizontal structures with steel beams due to its lightness, reliability and functionality. Three designs of fireproof suspended ceiling with silicate plates on cement binder are considered. A detailed description of the tested structures is given. Experiments were carried out to determine the fire resistance of the samples. The results of fire tests on suspended ceilings under standard fire temperature regime are presented in this study. It was found that the structures that have shown their effectiveness under the standard regime cannot satisfy the conditions of the hydrocarbon temperature regime. For the purpose of efficiency in the hydrocarbon regime and isolating the beams from the fire, in addition to fire-retardant plates, non-combustible heat insulation was used in the construction of the ceiling. The results of testing the ceiling with fire-retardant plates and rock wool when creating a hydrocarbon fire regime are given. It is shown that at the end of the fire exposure, the limiting state of the loss of bearing capacity and the loss of integrity was not fixed, visible changes during the test period was not found.

Аннотация. Подвесной потолок является эффективным способом огнезащиты горизонтальных конструкций перекрытий со стальными балками за счет своей легкости, надежности и функциональности. Рассмотрены три конструкции огнезащитного подвесного потолка с силикатными плитами на цементном вяжущем. Дано подробное описание испытываемых конструкций. Проведены эксперименты с целью определения огнестойкости образцов. Приведены результаты огневых испытаний подвесных потолков при создании стандартного температурного режима пожара. Получено, что конструкции, показавшие свою эффективность при стандартном режиме, не могут удовлетворить условиям углеводородного температурного режима. С целью эффективности при углеводородном режиме и изолирования балок от огня, кроме огнезащитных плит использована в конструкции потолка негорючая теплоизоляция. Приведены результаты испытания потолка с огнезащитными плитами и каменной ватой при создании углеводородного режима пожара. Показано, что на момент окончания огневого воздействия предельное состояние по потере несущей способности и по потере целостности не зафиксировано, видимых изменений в течение времени проведения испытания не обнаружено.

1. Introduction

Fires have a big impact on buildings and structures as directly when the fire is located on the site itself, and indirectly [1]. Therefore, the number of emergency actions [2] should include fire impacts arising from a fire, as well as the choice of space planning solutions [3] should be determined taking into account the requirements of fire safety. For example, the fire effect significantly changes the rigidity of steel beam-to-column connections [4], welded tubular joints are very defenseless without fire protection [5], and the

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aluminum parts of the structures are most exposed to melting during combustion [6]. In this way, the design of fire protection is a mandatory requirement in the design of structures [7, 8].

Protection of buildings and structures, equipment, structures of tankers and offshore platforms in the conditions of combustion of fire-hazardous and explosive substances at oil and gas facilities is an actual problem [9–11].

Until recently, in Russia, all tests of structures and materials were carried out only under conditions of a standard temperature regime, otherwise known as cellulose, whose combustion materials are wood, cloth, paper [12–14]. Fires resulting from the burning of petroleum products, as a rule, can be attributed to the so-called hydrocarbon fire, which is characterized by a rapid temperature rise, and is accompanied by a shock wave of flame on structures, fireproof coatings, combustible finishing and building materials [15, 16]. Materials and structures that have proven effective under standard conditions, as a rule, cannot provide the required level of protection under conditions of hydrocarbon fire [17].

The range of materials, burning of which refers to a hydrocarbon fire, is very wide. They can act not only pure hydrocarbons (gasoline and natural gases – methane, ethane, propane, butane, etc.), but also their organic derivative (alcohols, phenols, ketones), virtually all oil products, lubricants and varnishes, many plastics with a low oxygen index.

A detailed review of international standards for determining the fire resistance of structures under a hydrocarbon fire, as well as an analysis of technical regulations in the field of fire protection for ships and offshore platforms is given in [18].

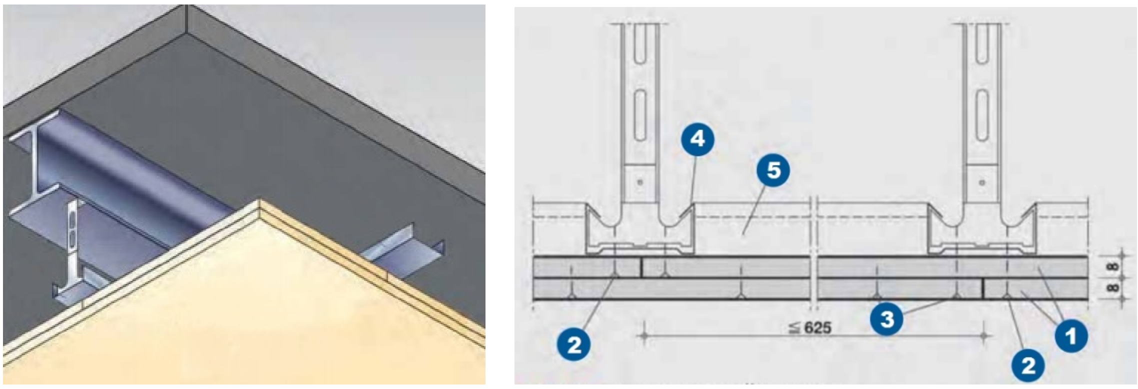
At present, there is a tendency to simulate a hydrocarbon fire in different software complexes in order to determine the effect of fire on various structures [19–23].

One of the important approaches for ensuring fire safety of buildings and structures is the use of a method for analyzing, assessing and managing the risk of an accident. This method allows to develop the most safe and at the same time economical design solution [24, 25].

The principle of passive fire protection in a hydrocarbon fire is to isolate the protected structure from fire. The insulation provides a thermal barrier, slowing the rate of heating of the steel and providing the required time for the fire extinguishing prior to the destruction of structures [26, 27].

One way to protect horizontal structural elements from the effects of a hydrocarbon fire is the fireproof suspended ceilings, which relate to constructive fire protection. The use of constructive fire protection is considered to be the most effective method, from the number used today to protect the structures of buildings and structures from the effects of fire and high temperatures in fires. In addition, when using this type of fire protection there are no wet processes and work can be carried out at any ambient temperature.

Suspended ceilings are used to protect horizontal structures of coatings and slabs with steel beams and are structural and functional elements. Important advantages of such fire protection are the ease of the suspended ceiling, as well as the reliability of the structure due to the formation of an air gap, which additionally increases the fire resistance limit [28].



1 – PROMATECT-H *t* = 10 mm plates in 2 layers; 2 – screws 4.2×25 pitch 150–200 mm; 3 – screws 4.2×35 pitch 200 mm; 4 – C-profile of floor structure CD 60×27×0.6 with anchoring; 5 – profile above the cross joint

Figure 1. The design of the fireproof suspended ceiling PROMATECT-H on metal I-beams (left) and a cross-section (right).

Also, fireproof suspended ceilings serve to protect against fire engineering communications systems, such as ventilation and air conditioning systems, electricity supply. By installing this type of ceiling, an independent fire compartment is created for communications, protecting them in the inter-ceiling space and ensuring their fire safety.

In addition to protecting structures with steel beams, fireproof suspended ceilings are also used to protect coatings from profiled sheets. In work [29], the influence of the gap size of the air layer on the fire resistance of the structure as a whole was investigated. Most of the studies are devoted to the development of either thin-layer fire retardant coatings [13, 30, 31], or constructive fire protection in the form of separate plate elements [26, 27], and holistic elements, such as a fireproof suspended ceiling, are given little attention.

In this work the designs of the suspended ceiling with fire resistant plates PROMATECT-H and PROMATECT-T were investigated. They are insensitive to moisture, large format and self-supporting. The difference in the name determines the possibility of using the hydrocarbon regime (PROMATECT-T). PROMATECT-T plates are used as cladding of elements and structures of tunnels, underground transport structures and any objects with increased requirements to heat load and resistance to aggressive environment, can be used both indoors and outdoors with increased wind load (including in the Arctic). PROMATECT-H plates serve as constructive fire protection of buildings and structures, are used indoors and can be an additional decorative element.

The fire retardant plates used in work belong to the class of fireproof plates on cement binder. Table 1 shows the characteristics of plates of other producers belonging to this class.

Table 1. The main properties of the plates on cement binder.

Producer	Promat	Promat	Knauf	PROZASK	PROZASK
Plate	PROMATECT-H	PROMATECT-T	AQUAPANEL Cement Board Outdoor	Firepanel	PYRO-SAFE AESTUVER-T
Composition (main components)	silicate plates on cement binder	silicate plates on cement binder	Portland cement, expanded clay sand, perlite, hydrophobic and other additives	Cement binder with light mineral filler	Cement binder, fiberglass, perlite
Density, kg/m³	870	900	1100-1200	1100-1200	980
Moisture content, %	6	5	-	-	7
Alkalinity, pH	12	10	12	12	12
Thermal conductivity, W/m°K	0.175	0.212	0.350	0.350	0.185
Moisture diffusion resistance, μ	20	5	66	66	-
Flexural strength, MPa	7.6	5	>10	5.4	7.5
Tensile strength, MPa	4.8	1.2	-	-	7.5
Compressive strength, MPa	9.3	4	-	-	-
Elastic modulus, MPa	4200 (longitudinal) 2900 (transverse)	1400	4000	-	4500
Combustibility	Non combustible	Non combustible	Non combustible	Non combustible	Non combustible
Fire temperature regime	standard	hydrocarbon	standard	hydrocarbon	hydrocarbon

* “-“ there is no information on the producer's website

PROMATECT-T plates are a product of Etex Building Performance, owner of Promat – the world's largest producer of flame retardant materials and high-temperature insulation. Thanks to their work, fire safety projects around the world have been implemented in civil and industrial construction, petrochemical, gas, nuclear and power engineering. In addition, the company is engaged in testing and certification of fire protection systems for steel, reinforced concrete, wooden structures and utilities. The assortment of fire resistant coatings Promat is presented by compositions of different type and purpose. This allows you to provide comprehensive protection for any object. The proposed fire retardant coatings are of high quality and at the same time cost-effective.

The work carried out tests of three systems of designs with fireproof ceilings:

– under standard temperature conditions, the ceiling was tested with a PROMATECT-H plate with a thickness of 8 mm in two layers (2×8 = 16 mm);

– under standard temperature conditions, the ceiling was tested with a PROMATECT-H plate with a thickness of 10 mm in two layers (10×2 = 20 mm);

– under hydrocarbon temperature conditions, the ceiling was tested with a 15 mm thick PROMATECT-T plate, fixed to the steel substructure in two layers (2×15 = 30 mm), with a thermal insulation layer of stone wool 200 mm thick with a density of 60 kg/m3.

The aim of the work was to select the thickness of the thermal insulation and the thickness of the fireproof ceiling slabs to obtain the test results for the fire resistance parameters in the hydrocarbon fire for at least 150 minutes.

2. *Methods*

Tests of prototypes of the construction of a fireproof suspended ceiling were carried out to determine the flame retardant efficiency of the samples presented in accordance with Russian State Standards GOST 30247.0-94 "Elements of building constructions. Fire-resistance test methods. General requirements" and GOST R 53298-2009 "Suspended ceilings. Fire-resistance test method".

The duration of the test was determined by the onset of the limit state by loss of integrity (E) and the loss of bearing capacity (R), depending on which of the limit states occurs earlier.

Initially, tests were carried out on a standard temperature regime to determine the limiting possibilities for the fire resistance of panels on cement binder

2.1. Fireproof ceiling test with standard temperature regime

Samples of the ceiling with a size of 2800×3000 mm consist of 8 mm thick plates on cement binder in 2 layers (2 samples) and 10 mm thick in 2 layers (2 samples) mounted on a frame of steel profiles. The frame with the help of suspensions attached to the bearing I-beams No. 20 and reinforced concrete floor slabs. The distance from the bottom of the beam to the ceiling is 160 mm.

In the fire chamber of the furnace, the standard temperature regime was maintained, characterized by the following relationship:

$$T - T_0 = 345 \cdot \lg\left(8t + 1\right), \tag{1}$$

where T is the temperature in the furnace, corresponding to the time *t*, °C;

T_0 is the temperature in the furnace before the onset of heat exposure (ambient temperature), °C;

t is the time calculated from the beginning of the test, min.

For the design of the ceiling with fire resistant panels 8 mm thick in 2 layers, the ambient temperature and relative humidity of the air during the first test were 25 °C and 69 %, respectively, in the second test these readings were equal to 26 °C and 64 %.

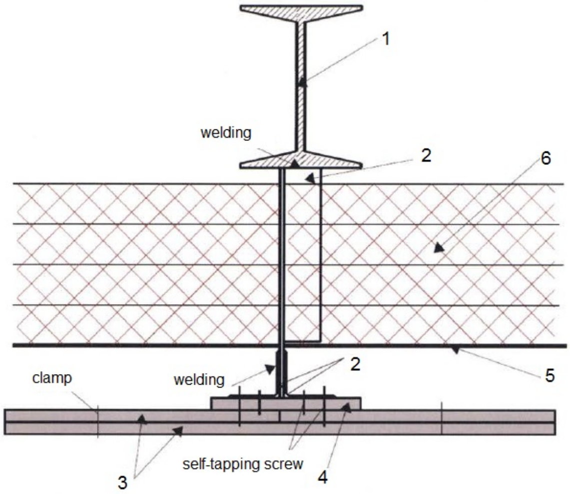
For the design of the ceiling with 10 mm thick flame retardant plates, the ambient temperature and relative air humidity in the first test were 15 °C and 66 %, respectively, in the second these readings were 14 °C and 65 %.

The temperature in the fire chamber of the furnace and on the test samples is measured using furnace thermocouples, and the vertical deformations of the samples during the test are measured with a deflectometer.

2.2. Fireproof ceiling test with hydrocarbon temperature regime

For the tests, 2 samples of the design of the fireproof suspended ceiling with dimensions of 5000×3000×545 mm were presented. The height is indicated taking into account the metal prefabricated substructure made of the rolling profiles of the angular and I-section sections.

A schematic diagram of the design of a prototype of a fireproof suspended ceiling is shown in Figure 2.



**1 – beam 20B1; 2 – corner L 40×4; 3 – plate PROMATECT-T *t* = 15 mm;
4 – strip from the plate PROMATECT-T *t* = 15 mm, width 160 mm; 5 – metal mesh 100×100 wire diameter 5 mm; 6 – rock wool slabs *t* = 50 mm, 4 layers**

Figure 2. Schematic diagram of the design of a prototype of a fireproof suspended ceiling.

The metal frame of the suspended ceiling was made by installing vertical supports welded to the beams of the I-section profile No. 20B1 in accordance with Russian State Standard GOST 26020-83 (reduced thickness of metal – 3.4 mm), set in the number of 5 pieces. To these supports longitudinal guides were welded from the double angle 40×4 mm in accordance with Russian State Standard GOST 8509-93, and in the transverse direction the guides were connected by double angles 40x4 mm welded to the side by side elements. Thus, the nominal pitch of the metal elements of the framework of the fireproof suspended ceiling, forming a flat welded cage for fixing the plate materials of the enclosing part, was 626–1250 mm.

At the bottom of the flat welded cage of the metal frame of the suspended ceiling, strips of width 160 mm, made of plates on cement binder 15 mm thick, fastened to the metal sub-structure with self-tapping screws, were fastened. After that, over the metal elements of the frame, a two-layer covering was made with plates on cement binder 15 mm thick (2×15 = 30 mm), fasteners of which were made with self-tapping screws and staples installed with a pitch (300 ± 10) mm.

At the end of the assembly of the enclosing part of the suspended ceiling from panels on cement binder, a metal grid with a cell of 100×100 mm made of a wire of 5 mm and 4 layers of heat insulation boards made of rock wool 50 mm thick and with a density of 60 kg/m^3 was laid along the top of the steel angles. The total thickness of the thermal insulation layer was 200 mm.

To prevent the penetration of the flame around the perimeter of the sample, the insulation was laid, covering the cracks between the lining of the furnace and the plates of the enclosing part of the suspended ceiling.

In order to simulate the construction of the ceiling and ensure the thermal regime of heating the metal structures of the suspended ceiling protected by the enclosure, the steel I-beam beams were laid with reinforced concrete covering plates. On the perimeter, the sides of the prototype were covered with slabs of incombustible mineral wool insulation. To simulate the mode of movement of air in the allocated space above the fence of the fireproof suspended ceiling, along the end parts of the samples, a device of openings 300×500 mm in size was provided.

The ambient temperature and the relative humidity of the air during the first test were 21 °C and 50 %, respectively, in the second, these readings were equal to 23 °C and 52 %. The speed of air movement in both tests did not exceed 0.5 m/sec.

2.3. Test procedure

The experimental samples were placed on an experimental setup and subjected to unilateral thermal action.

In the fire chamber of the furnace, a hydrocarbon temperature regime was created in accordance with Russian State Standard GOST R EN 1363-2-2014, characterized by the following relationship:

$$T = 1080 \cdot \left(1 - 0.325\mathrm{e}^{-0.167t} - 0.675\mathrm{e}^{-2.5t}\right) + 20, \tag{2}$$

where T is the temperature in the furnace, corresponding to the time t, °C;

t is time, calculated from the beginning of the test, min.

The temperature in the fire chamber of the furnace was measured by furnace thermocouples, evenly distributed along the length of the sample at six locations.

On the experimental samples, the temperature was measured by thermocouples installed in an amount of 9 pieces on the I-beams of the metal skeleton of the suspended ceiling in the middle of their spans (with the exception of the two outer beams), in accordance with the requirements set out in 5.4.4 Russian State Standard GOST R 53295-2009.

3. Results and Discussion

3.1. Ceiling test results at a standard temperature regime

Curves of temperature changes in the controlled points when creating a standard temperature regime are shown in Figure 3.

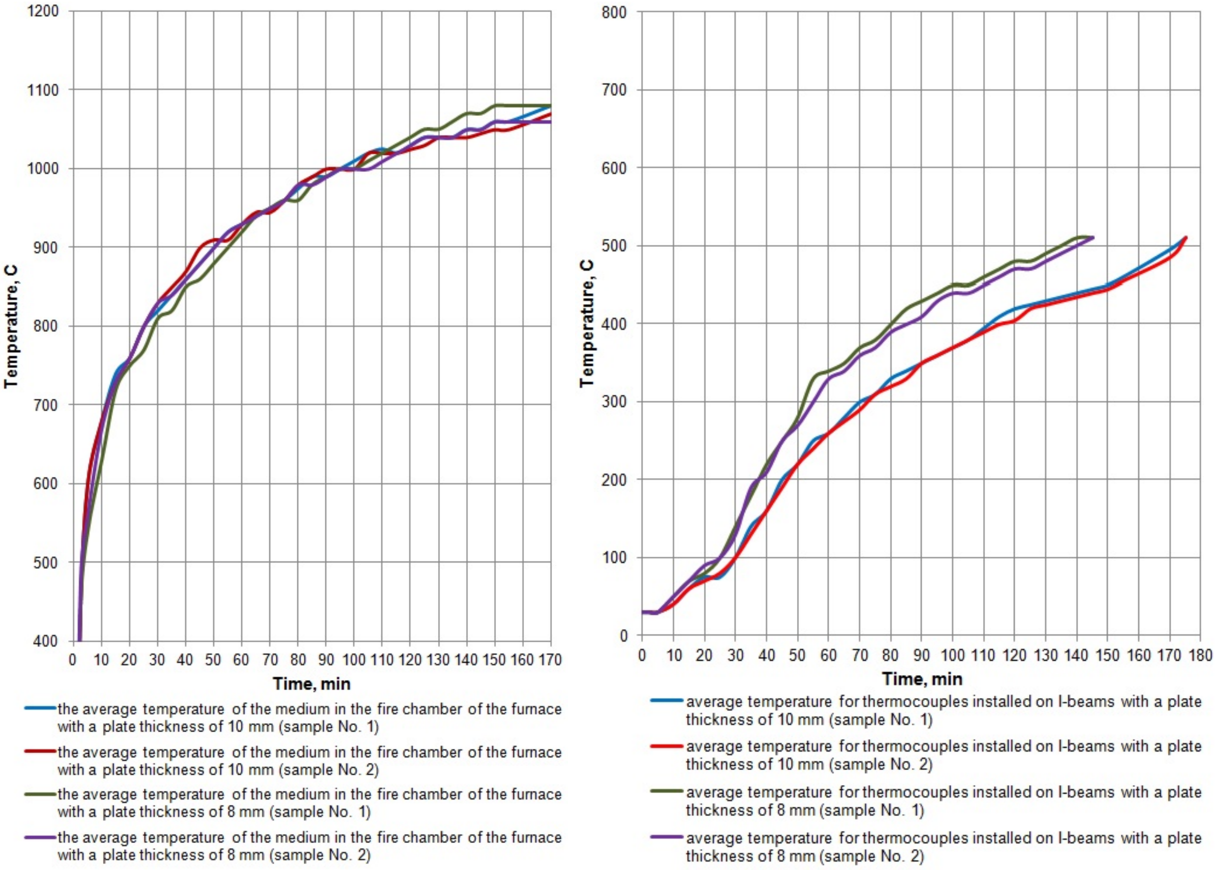


Figure 3. Temperature curves in the fire chamber of the furnace (left) and on I-beams of steel frames (right) in standard regime.

Table 2. The results of monitoring the tests for the construction with a plate thickness of 8 mm.

Sample 1		Sample 2	
Time	The results of monitoring	Time	The results of monitoring
0’	The beginning of the test	0’	The beginning of the test
5’	Strong emission of steam from the structure	15’	Steam emission from the structure
30’	Deflection 0 mm	45’	Deflection 0 mm
45’	Steam emission decreased	50’	Steam emission decreased
90’	Deflection 2 mm	95’	Deflection 2 mm
135’	Deflection 4 mm	140’	Deflection 4 mm
148’	The test is over	146’	The test is over

As a result, the limit state was achieved by loss of bearing capacity and amounted to 136 minutes for sample 1, 142 minutes for sample 2.

Table 3. The results of monitoring the tests for the construction with a plate thickness of 10 mm.

Sample 1		Sample 2	
Time	The results of monitoring	Time	The results of monitoring
0’	The beginning of the test	0’	The beginning of the test
16’	Smoke emission from the junction of reinforced concrete slabs	17’	Smoke emission from the junction of reinforced concrete slabs
40’	Deflection 5 mm	45’	Deflection 5mm
61’	Deflection 10 mm	65’	Deflection 15 mm
110’	Deflection 15 mm	95’	Deflection 18 mm
166’	Deflection 18 mm	140’	Deflection 19 mm
175’	The test is over	176’	The test is over

As a result, the limit state was reached by loss of bearing capacity and amounted to 172 minutes for sample 1, 175 minutes for sample 2.

3.2. Ceiling test results at a hydrocarbon temperature regime

Curves of temperature changes in the controlled points when creating a hydrocarbon temperature regime are shown in Figure 4.

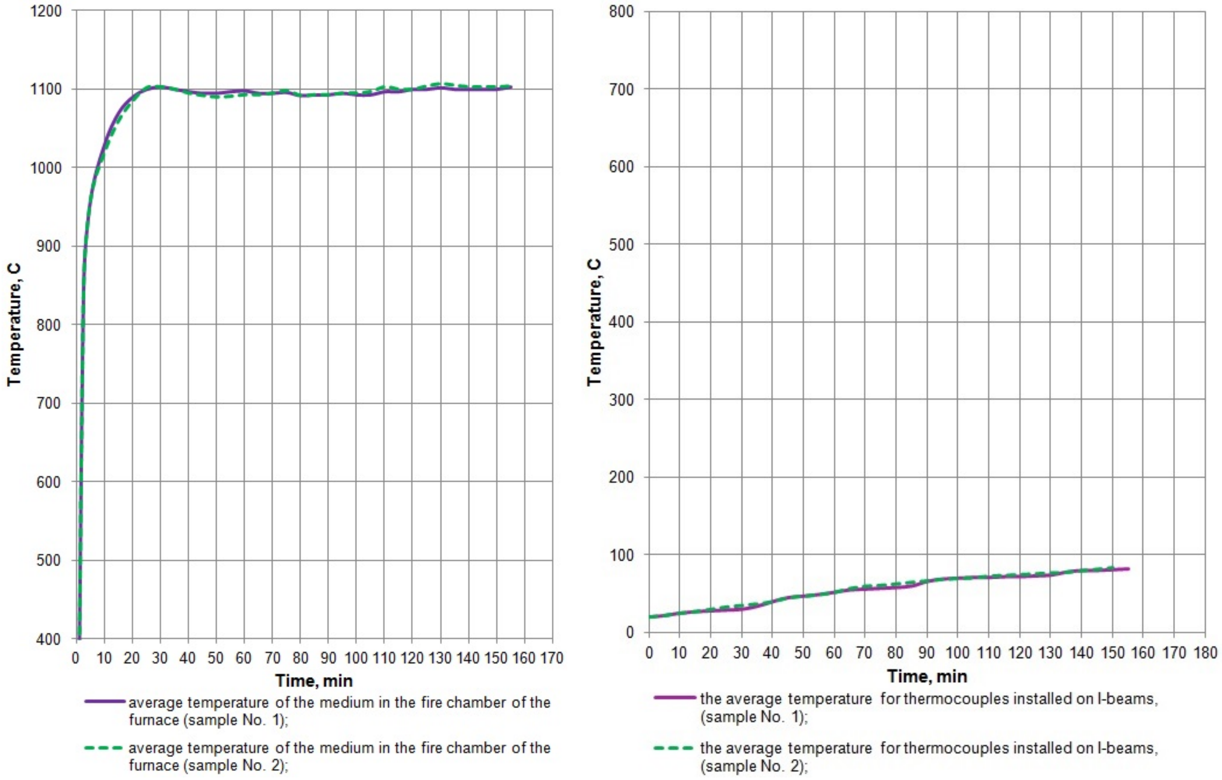


Figure 4. Temperature curves in the fire chamber of the furnace (left) and on I-beams of steel frames (right) in hydrocarbon regime.

According to agreement with the producer, the tests were stopped at the 155th minute. During the testing of the prototypes of the fireproof suspended ceiling, no visible changes were observed in the state of the protecting parts of the plates on cement binder.

At the time of the end of the fire impact (155 min), the wall part of the plates on cement binder did not collapse. Displacements and violations of the integrity of the layer of insulation from rock wool were not fixed. The deformation of the steel elements of the skeleton of the suspended ceiling has not been observed.

At the time of the end of the fire action, the average temperature for the thermocouples installed on the steel I-beams of the frame was 75 °C and 82 °C for the 1st and 2nd samples, respectively.

Thus, none of the limiting states for which the tests were conducted was achieved during the time of fire tests.

Partial collapse of the plates of the fencing part of the suspended ceiling was recorded after the cooling of the prototypes.

Figure 5. A sample of the ceiling design before the test (left) and partial collapse of the enclosing part of the suspended ceiling during cooling (right)

The tests of the fireproof suspended ceiling showed that the design of the ceiling, tested in the standard regime, will not be able to satisfy the conditions of hydrocarbon combustion, with a stronger effect of the hydrocarbon regime, the critical temperature of 500 °C will be reached much earlier. In order to be effective in the hydrocarbon regime and isolate the beams from the fire, it is necessary, in addition to fire-retardant plates, to use non-combustible heat insulation in the ceiling design and increase the own thickness of the plates on cement binder, which made it possible to ensure the required fire resistance of the structure.

The fireproof suspended ceiling showed its effectiveness not only under standard conditions [28, 29], but also under conditions of hydrocarbon fire. Therefore, testing this design under different conditions is necessary to create a complete picture of the behavior of the suspended ceiling, which will allow more extensive use this type of passive fire protection for horizontal structures of ceilings and slabs. Most of the studies are devoted to the development of either thin-layer fire retardant coatings [13, 30, 31], or constructive fire protection in the form of separate plate elements [26, 27], and holistic elements, such as a fireproof suspended ceiling, are given little attention.

4. Conclusions

The study leads to the following conclusions:

1) Testing of samples of a flame-retardant suspended ceiling made of PROMATECT-H plates 16 mm thick, provided that a standard regime was created in the fire chamber of the furnace, was completed by reaching the limit state for loss of bearing capacity after 136 min and 142 min for samples 1 and 2;

2) Testing of samples of a flame-retardant suspended ceiling made of PROMATECT-H plates with a thickness of 20 mm, provided that a standard regime was created in the fire chamber of the furnace, ended with reaching the limit state of loss of bearing capacity after 172 min and 175 min for sample 1 and 2;

3) Testing of samples of a flame-retardant suspended ceiling made of PROMATECT-T plates with a thickness of 30 mm, with an insulating layer of rock wool, provided that a hydrocarbon temperature regime was created in the fire chamber of the furnace did not end with reaching the limit state of loss of bearing capacity of the structure and the occurrence of ultimate strains at the time the end of fire exposure (155 min). The critical temperature of 500 °C during the tests (155 min) on the steel I-beams of the samples was not reached (the average temperature for thermocouples at the time of ending of the fire exposure was 75 °C and 82 °C, for the 1st and 2nd sample, respectively);

4) The designs of the fireproof ceiling using plates on cement binder have proven their effectiveness under standard temperature regime;

5) To achieve the required degree of fire protection in hydrocarbon fire conditions, it is necessary to use plates on cement binder with a greater thickness compared to structures that have proven to be effective in a standard regime, as well as to use non-combustible insulation.

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