Fire protective dry plaster composition for structures in hydrocarbon fire

Огнезащитный штукатурный состав для конструкций в условиях углеводородного горения

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Key words: oil and gas facilities; steel structures; fire resistance limit; passive fire protection; fire protection means; hydrocarbon fire

Key words: сооружения нефтегазового комплекса; стальные конструкции; предел огнестойкости; пассивная огнезащита; средства огнезащиты; углеводородный пожар

Abstract. The result of the combustion of fire hazardous materials at the facilities of the oil and gas complex is extensive fires, characterizing the rapid temperature rise, and as a result the destruction of load-bearing structures occurs. The dynamics of the development of such fire type requires a different approach to test the structures in order to determine the limit of fire resistance. The article presents European and American normative documents that contain methods for testing structures taking into account the requirements for the hydrocarbon temperature regime of a fire. I-steel cross-sections with flame retardant coating "Fendolite MII" are tested, and the fire resistance of these structures is defined. Conclusions on the need to conduct numerous fire tests with different types of fire protection under a hydrocarbon fire regime in Russia were made in order to obtain the necessary experimental database sufficient to create a unified methodology for calculating and introducing it into national standards.

Annotaция. Результатом сгорания пожароопасных веществ на объектах нефтегазового комплекса являются обширные пожары, характеризующиеся стремительным ростом температуры, и как следствие разрушение несущих конструкций. Динамика развития такого пожара требует иной подход к проведению испытаний конструкций с целью определения предела огнестойкости. В статье приведены европейские и американские нормативные документы, содержащие методы испытаний конструкций с учетом требований к углеводородному температурному режиму пожара. Проведены испытания стальных колонн двутаврового сечения с огнезащитным покрытием "Fendolite MII", и определен предел огнестойкости данных конструкций. Сделаны выводы о необходимости проведения в России многочисленных огневых испытаний конструкций с различными типами огнезащиты в условиях углеводородного режима пожара с целью получения необходимой экспериментальной базы данных, достаточной для создания единой методики расчета и внедрения ее в национальные стандарты.

1. Introduction

Explosive combustion of fire hazardous substances at oil and gas facilities is the main cause of destruction of buildings and structures, as well as tanks, equipment, tankers and offshore platforms. The subsequent extensive fires resulting from the burning of petroleum products, as a rule, can be attributed to the so-called hydrocarbon fire.

In the articles [1, 2] the necessity of introduction and subsequent use for fire tests of building structures for fire resistance of a new temperature regime of a fire taking into account the real fire conditions is substantiated [3].

Hydrocarbon fire is characterized by a rapid temperature rise: the average surface temperature of the flame during the combustion of petroleum products reaches 1000 °C, which is much higher than the temperature of a conventional (cellulose) fire.
Similar to the standard fire regime, in which not only cellulose can be a combustible material [4], combustion of a whole group of substances similar in ease of ignition and type of combustion is a hydrocarbon fire. This group of substances consists from not only pure hydrocarbons (petrol and natural gases – methane, ethane, propane, butane, etc.), but also from their organic derivative (alcohols, phenols, ketones), virtually all petroleum products, lubricants, paint and varnish materials, many plastics with a low oxygen index.

The dynamics of the development of hydrocarbon fire requires a different approach to ensuring fire resistance of building structures. Most fire-retardant and fire-resistant building structures have proved their effectiveness under the conditions of a standard fire [5-7]. In foreign publications, many studies are devoted to fire protection of steel structures. One of the papers is devoted to the calculation of the operation of a steel plate under high-temperature conditions [8]. However, the structures studied under these conditions can not provide the same characteristics under conditions of a hydrocarbon fire [9].

An important approach for ensuring the safety of petrochemical production is the use of the risk analysis method, which allows to determine the places of the most probable occurrence of an accident, and assess their consequences. This makes it possible to adequately protect the structures from special loads caused by hydrocarbon combustion. The method of risk analysis enables the development of safer and at the same time cost-effective design solutions, including for the protection of structures. This method was adopted in Russia, Great Britain, USA, Norway, Australia, France [10-15].

Recently, modeling of hydrocarbon fires in software complexes has been used to determine the duration of fires in different areas [16], and empirical relationships connecting the values of the fire resistance limits of structures in the hydrocarbon and standard temperature regimes of a fire [17], which makes it possible to approximately estimate the fire resistance limits of structures under the hydrocarbon fire condition, when the fire resistance limits are known at the standard fire regime, and thereby facilitate the testing of the structure.

Traditionally, researches in the field of fire safety is focused on providing the required degree of fire resistance of buildings, and a little attention has been paid to the construction of bridges. The works [18, 19] are aimed to develop knowledge about the behavior of steel bridges under the influence of the hydrocarbon fire regime, which occurs, for example, in the collapse or fire of a gasoline tanker.

On the international scale, the Technical Committee 92 "Fire Safety" of the International Organization of Standardization (ISO) is engaged in the improvement and unification of the methodology for testing structures for fire resistance. Within the framework of this committee and on the basis of international cooperation, a standard of ISO 834-75 "Fire resistance tests. Elements of building constructions" (in the updated version – ISO 834-1: 1999) has been developed for the method of testing the building structures for fire resistance, which is the methodological basis for conducting such tests, including in Russia.

In determining the fire resistance of structures under the conditions of the hydrocarbon fire regime, standards such as UL 1709 (USA) [20], ASTM E 1529-14A "Standard test methods for determining effects of large hydrocarbon pool fires on structural members and assemblies" (USA) and European EN 1363-2: 1999* "Fire resistance tests – Part 2: Alternative and additional procedures", DIN 4102-2-1977 "Fire tests on building materials and structures. Methods for determination of the fire resistance of load bearing elements of construction" (Germany), BS 476-20: 1987 "Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles)" (Great Britain) [21]. In most cases, these standards are used to assess the stability and fire resistance of load-bearing structures of railway and automobile tunnels, as well as to evaluate the efficiency of external technological installations for the extraction, processing and transportation of gas, oil and petroleum products on offshore oil platforms. They determine the criteria for the resistance of fireproof coatings in a hydrocarbon fire. Especially for evaluating the effectiveness of fire protection of pipelines, the method of "direct impact" of the jet flame is additionally applied. The criterion for the effectiveness of the fireproof composition is the time from the beginning of the test to the onset of the limit state.

It should be noted that, according to the research of the American insurance and engineering company Global Asset Protection Services LLC (GAPS), the values of the consumption and thickness of coatings for fire-retardant products for structures according to methods of ASTM E-119 "Fire tests of building construction and materials" and UL 1709 under the hydrocarbon fire regime had a significant difference and the data obtained by these methods, respectively, required correlation between themselves [22].

Up to date, Russia has not developed a regulatory framework for fire protection of load-bearing steel structures in conditions of hydrocarbon combustion. In 2015, the normative documentation introduced the concept of a "hydrocarbon curve" [23]. This standard is identical to the European regional standard EN 1363-2: 1999.

According to [23] the hydrocarbon temperature regime is an alternative to the standard temperature regime and takes into account the real fire conditions for burning hydrocarbon fuels.

Graphical representation of the hydrocarbon fire curve and other temperature regimes is shown in the figure:

Figure 1. Fire curves. 1 – standard time-temperature curve; 2 – hydrocarbon curve; 3 – external fire exposure curve; 4 – slow heating curve

The curve for cellulose combustion is also called the standard combustion curve. As can be seen from the figure, the hydrocarbon scenario of the fire development is fundamentally different from the cellulose fire: the temperature jump is much sharper and the temperature effect is higher. In such conditions, traditional fire-retardant materials do not provide the necessary level of fire-protective efficiency.

Despite of the urgency of the problem of protection in the conditions of hydrocarbon combustion for Russia, this normative document of the Russian Federation became the first official standard in this field. However, it only establishes a temperature regime, and the test methods for various types of products under the conditions of hydrocarbon combustion are only to be developed. Despite the absence of requirements and norms in the Russian Federation for the limits of fire resistance of structures under the conditions of a hydrocarbon fire, Russian manufacturers voluntarily conduct tests of the available fire protection means according to the procedures given in various foreign regulatory documents, which is an additional competitive advantage, but because of the high costs applied only for a specific security object.

One way to protect structures is passive fire protection - solutions used to prevent the occurrence and spread of fire. The most common means of passive fire protection include special refractory compounds, paints, impregnations, varnishes and fireproofing plasters [24], which can significantly reduce the likelihood of fire and spread of fire. As a passive protection against a hydrocarbon fire, 2 types of materials are used [25]:

- Lightweight cement coatings (usually based on portland cement and lightweight aggregates)
- Intumescent paints and varnish coatings

Lightweight cement coating is a relatively inexpensive material, but the application works in several stages, which ultimately increases the cost of using this type of fire protection. It is not used in rooms with a high humidity level.

Intumescent coating protects the structure by forming a heat-insulating protective layer at high temperatures. This coating is easier to apply, and to increase the protection time of steel it can be applied in several layers.

In order to increase the operational characteristics of intumescent coatings, such as durability, elasticity, homogeneity of the foam layer being formed, additional additives are applied to the standard formulations of intumescent coatings [26].

Intumescent coatings are used for protection against hydrocarbon fires, mainly on an epoxy basis. Since the epoxy has a very high resistance to almost any chemical attack, this type of product adds to its

fire-retardant characteristics an even higher level of anti-corrosion protection. In the article [27] the influence of external factors such as ultraviolet radiation, humidity, temperature changes, seawater, on the flame retardant properties of epoxy coatings examines. It is determined to what extent the protective properties of coatings in aggressive environments are reduced. Among the epoxy fireproof materials, the most common are "Jotachar 1709", "Chartek 7", "Chartek 8", "Interchar 212", "Firetex M90".

Another type of intumescent coating is a silicone-based coating. In work [28], the effect of clay as a filler on the fire resistance of a coating as a whole is considered. In [29], a new test method was developed to determine the strength of intumescent coating in a fire test and tests were conducted for epoxy and silicone based coatings.

The purpose of this paper is to examine the behavior of the "Fendolite MII" coating in the hydrocarbon combustion regime. "Fendolite MII" is a dry plaster composition based on expanded vermiculite and portland cement, used to increase the fire resistance of bearing steel and reinforced concrete structures, equipment, tanks, pipelines, etc. in civil and industrial construction, at chemical and petrochemical facilities, fuel and energy complex and in tunnels [30].

Figure 2. Coating "Fendolite MII" on an I-beam and on steel elements

Table 1. Properties and performances of "Fendolite MII"

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color and finish</td>
<td>Off-white, monolithic, spray texture. May be floated or roller finished</td>
</tr>
<tr>
<td>Minimum practical thickness</td>
<td>8 mm when unreinforced, 15 mm when reinforced</td>
</tr>
<tr>
<td>Theoretical coverage</td>
<td>62 m²/tonne at 25 mm thickness</td>
</tr>
<tr>
<td>Cure</td>
<td>By hydraulic set</td>
</tr>
<tr>
<td>Initial set</td>
<td>2 to 6 hours at 20°C and 50% RH</td>
</tr>
<tr>
<td>Density (nominal)</td>
<td>775 kg/m³ ±15% (when dry and in place)</td>
</tr>
<tr>
<td>Combustibility</td>
<td>Non-combustible to BS476:Part 4</td>
</tr>
<tr>
<td>Smoke generation</td>
<td>Does not contribute to smoke generation</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.19 W/mK at 20°C</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>Does not promote corrosion of steel. However, a primed substrate is recommended for long term corrosion resistance, particularly when the structure is to be fully exposed to the elements</td>
</tr>
<tr>
<td>pH value</td>
<td>12.0-12.5</td>
</tr>
<tr>
<td>Sound absorption</td>
<td>Noise reduction coefficient (NRC) 0.35</td>
</tr>
</tbody>
</table>

Figure 3. Sample cross-section
The object of the further test was 2 samples of steel columns with fireproof coating "Fendolite MII", which are rolled I-beams. The reduced thickness of the column metal is 6.3 mm.

**Table 2. Characteristics of rolled I-beam profile**

<table>
<thead>
<tr>
<th>Profile characteristic</th>
<th>Dimension, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>298</td>
</tr>
<tr>
<td>b</td>
<td>299</td>
</tr>
<tr>
<td>S</td>
<td>9</td>
</tr>
<tr>
<td>t</td>
<td>14</td>
</tr>
<tr>
<td>r</td>
<td>18</td>
</tr>
</tbody>
</table>

Material of the rolled I-beam is steel grade S345. Mechanical characteristics for the thickness t=14 mm are given in Table 3.

**Table 3. Mechanical characteristics steel grade S345**

<table>
<thead>
<tr>
<th>Mechanical characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength, MPa</td>
<td>325</td>
</tr>
<tr>
<td>Tensile strength, MPa</td>
<td>470</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>21</td>
</tr>
</tbody>
</table>

2. Methods

Tests of prototypes of steel columns with a flame retardant "Fendolite MII" on the fire impact in order to determine the fire resistance limit are performed in accordance with Russian State Standards GOST 30247.0-94 "Construction structures. Test methods for fire resistance. General requirements", GOST 30247.1-94 "Construction structures. Test methods for fire resistance, bearing and enclosing structures" provided that a hydrocarbon temperature regime is created in the fire chamber of the furnace.

According to the "Technological Regulations for the design and manufacture of works on the installation and operation of a coating based on a fire retardant mixture "Fendolite MII" to improve the fire resistance of metal structures", the application of a fire-protective coating is carried out on one layer of anticorrosion primer with a thickness of 0.05 mm, in two layers, fire retardant coating with steel plaster mesh. Thus, the average thickness of the dry coating layer for performing fire tests in a hydrocarbon fire is 30 mm for the 1st and 2nd prototype.

Experimental samples are installed in the fire chamber of the furnace and subjected to a four-sided thermal action. The furnace generates a hydrocarbon temperature regime, characterized by the dependence (1):

\[
T = 1080 \cdot (1 - 0.325 e^{-0.167t} - 0.675 e^{-2.5t}) + 20
\]

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

\( t \) – time, calculated from the beginning of the test, min.

Tests of load-bearing elements must be carried out under load. In this paper, the effect of a static load equals to 294 kN (30 tons) was taken into account under the condition of vertical central compression with hinge support on one side and rigid fixing on the other side of the column. The load is established 60 minutes before the start of the test and is maintained constant (with an accuracy of not less than ± 5 %) during the entire duration of the fire impact.

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

For load-bearing vertical bar structures, the limit state for a fire resistance test in accordance with 8.2 of Russian State Standard GOST 30247.1 is loss of bearing capacity (R) due to collapse of the structure or occurrence of ultimate deformations. According to Appendix A of Russian State Standard GOST 30247.1, the maximum vertical deformation for a given column is 30 mm, the rate of increase of vertical deformation is more than 10 mm/min.
3. Results and discussion

During the tests in the external state of the flame retardant coating "Fendolite MII", applied to the prototypes of the steel columns, no visible changes were recorded.

Figure 4. Appearance of the experimental image of a steel column with a flame retardant "Fendolite MII" after the fire impact (sample No. 1. view of the technological opening of the fire chamber)

The average temperatures in the fire chamber corresponded to the dependence (1). Curves of temperatures and vertical deformations changes of prototypes of steel columns with a flame retardant coating "Fendolite MII" are shown in Figure 4.

Figure 5. Curves of temperature changes and vertical deformations of prototypes of a steel column with a flame retardant coating "Fendolite MII" in the fire chamber of the furnace

On the 124th minute of the 1st and 126th tests of the 2nd test, the prototypes of steel columns passed to the limit state, characterized by a rapid increase in vertical deformation and not the ability of the design to accept a test load equal to 294 kN (30 tons).

At the time when the prototype limit state reached the loss of load capacity of the structure (R), the average temperature of the thermocouples (critical temperature) established on the metal of the test samples was 710 °C and 707 °C for the first and second samples.

Accordingly, the fire resistance limit according to the loss of bearing capacity (clause 8.1.1 and Annex A to Russian State Standard GOST 30247.1-94) of the construction of an I-steel column of height (3000 ± 10) mm with a reduced metal thickness of 6.3 mm with a flame retardant coating "Fendolite MII" at an average thickness of the dry coating layer of 30.0 mm, tested under the action of a static load equal to 294 kN (30 tons), provided the hydrocarbon temperature regime in the fire chamber of the furnace, was 125 minutes, which shows the significant ability of a fire-retardant coating "Fendolite MII" hydrocarbon type resists combustion, significantly exceeding the standard fire temperature regime.

For buildings and structures of the I degree of fire resistance according to Russian normative document SP 2.13130.2012 "Fire protection systems. Provision of fire resistance of protection facilities" the required fire resistance of load-bearing structures is 120 min, which means that the coating under investigation is capable of providing maximum regulatory requirements, but for a standard fire regime. At present, the standardization of fire resistance limits for the hydrocarbon fire regime is absent, the testing process goes randomly and leads to additional costs for manufacturers of fire protection means.

Plastered fire retardant compositions based on portland cement are the first in use as a flame retardant, the second is epoxy compositions [21].

According to the official websites of some companies that reported test results for fire retardant products for building structures tested for fire resistance under hydrocarbon fire, and UL 1709 certificates available in the open online database of Underwriters Laboratory [31] the reduced thickness of columns (column W10 x 49 according to the American classification) is about 6 mm. The thickness of the coating layer with a flame retardant efficiency of 120 minutes averages 30 mm. For example, for "Chartek 7", these data are 15 mm (epoxy base), for coating on the basis of portland cement "Pyrocurete 214" – 28.6 mm [27-29].

To use the correctly selected passive fire protection in conditions of hydrocarbon fire, and accordingly the most effective protection of objects at risk of this fire, there is a need to introduce a calculation procedure to determine the fire resistance of structures in the hydrocarbon combustion condition. To do this, it is necessary to collect and systematize the database for testing various types of load-bearing elements using different types of fire protection.

In the future, it is planned to test steel columns under different loads, with other reduced metal thicknesses to create an integral picture of the behavior of the fire-retardant coating under conditions of hydrocarbon combustion.

4. Conclusions

The results of experimental studies have shown that the fire resistance limit due to the loss of the load-carrying capacity of the I-section steel column with the "Fendolite II" flame retardant coating, with an average dry film thickness of 30.0 mm, tested under a constant load of 294 kN (30 tons) the condition for creating a hydrocarbon temperature regime in the fire chamber of the furnace, was 125 minutes.

As a result of the work, conclusions on the need to create a national regulatory framework with a clear regulation of the test methods for designs and the relevance of research on passive fire protection in hydrocarbon combustion were made.

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