Article

Structural Fire Protection of Steel Structures in Arctic Conditions

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Abstract: Most structures in the Arctic and Antarctic for oil and gas production are offshore stations, tankers, modules, steel supporting, and enclosing structures, which need to be protected against both cryogenic spills and fire exposure. Oil and gas industry facilities have products of high flammability and explosiveness, which in the case of ignition make it possible to develop a fire along the hydrocarbon curve, accompanied by a sharp jump in temperature and the formation of excessive pressure. This article discusses possible structural fire protection for metal structures in the Arctic region. Three different structural fireproofing materials are presented using super-thin basalt fiber (STBF) as an example. Tests of steel structures with fire protection are demonstrated, as a result of which the time from the beginning of cryogenic exposure to the limit state of samples is determined, and after the time from the beginning of thermal exposure to the limit state of samples under the hydrocarbon temperature regime is determined. An assessment of various flame retardants with values up to 120 min, which can be used in arctic climate conditions, was carried out. It was found that the most effective coatings are materials prepared on the basis of STBF.

Keywords: steel structure; oil and gas facility; super-thin basalt fiber (STBF); hydrocarbon fire; endothermic mat; cryogenic and fire exposure

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1. Introduction

The Arctic climate is the most severe with absolute minimum winter temperatures from -54°C to -71°C [1]. Buildings and structures in the Arctic and Antarctic are Arctic stations and plants for the production, refining, and transportation of products of the oil and gas facility, the steel load-bearing and enclosing structures of which need to be protected with special materials, in particular fire retardants to increase their fire resistance limits, also after the filling of cryogenic liquid, such as liquid natural gas (LNG) [2–4]. The ISO 20088-1:2016 [5], ISO 20088-2:2020 [6], and ISO 20088-3:2018 [7] series of standards regulate the effects of cryogenic liquid (simulation of liquefied hydrocarbon spills) on fire protection on steel structures. Further, the structure with fire protection is tested according to UL 1709 [8] or EN R 1362-2 (EN 1363-2:1999) [9,10] for the impact of a hydrocarbon fire regime (unambiguous requirements for the fire resistance limits of structures to the impact of hydrocarbon fire regime are presented only for structures of drilling platforms and offshore installations) [11]. There are precedents of fires at the stations. For example, the world's largest catastrophe at the Piper Alpha platform in the North Sea on 6 July 1988, resulted in a series of explosions in the main oil and gas pipelines [12,13]. Deepwater Horizon, which took place on 20 April 2010, is one of the biggest technological disasters resulting in human losses and destruction as well as a negative impact on the environment [14]. Fires also occur at Arctic stations, the bearing elements of which are steel structures. For example, in 2012 a fire destroyed the Antarctic research station Comandante Ferraz, located on King George Island in Antarctica [15].

In arctic conditions, the following requirements are presented for the fire protection of steel structures: saving reliability (operability) in the Arctic climate for at least 10 years, and

“dry” installation without liquid phase, resistance to extreme effects in the form of liquid hydrocarbon spills, with their further ignition and the development of a hydrocarbon fire mode [16–26].

Optimal solutions for the protection of steel structures in fires were considered in [27] with the example of intumescent coatings. In [28], the effect of the main components of intumescent coating on the flame retardant properties was studied. An important component of intumescent coating is the binder, which has the following main functions: elasticity, hardness, and durability. On the whole, the listed physical and chemical characteristics allow to obtain a quality, defect-free, durable flame retardant coating. One of the important aspects of intumescent coating is its relative water solubility [29]. Thus, when using a surface exposed to water or a humid environment, the effectiveness of base protection is reduced due to the possible washout of the compounds responsible for bloating. In [30], I-beam steel columns with a plaster fireproofing coating were tested under hydrocarbon fire conditions with a fire protection efficiency of 120 min, but “wet” application under Arctic conditions is impossible. A numerical evaluation of the effectiveness of different configurations of passive fire protection (PFP) layers in marine topsides structures exposed to localized fires is presented in [31]. The paper describes the use of a simplified methodology in evaluating the thermo-mechanical behavior of an offshore structure under high temperatures, taking into account the presence of a PFP layer. A series of tensile tests of two types of mineral wool materials at room temperature and at high temperatures in fire conditions is demonstrated in [32]. The mechanical properties were verified using modified methods and a database was created to apply a series of nonlinear structural and thermal finite-element analyses of the PFP bulkhead marine system.

The scheme of means and methods of fire protection of steel structures is shown in Figure 1, demonstrating that the most preferable means of fire protection in the Arctic climate is the application of structural fire protection, the main advantage of which is the “dry” installation and high fire resistance.

Figure 1. Means and methods of fire protection of steel structures.

A prospective basis for thermal insulation materials and products is super-thin basalt fibers (STBF) made exclusively from basalts without admixtures of other minerals [33]. Thermal insulation products based on STBF practically do not have an alternative in the energy shipbuilding and aircraft industry, in construction, of which the main area of application is to increase the fire resistance of structures. Due to thermal properties, durability, non-combustibility, resistance to low and high temperatures and vibrations, environmental friendliness, fire resistance, and low hygroscopicity, thermal insulation products based on STBF are much superior to their analogues. Thus, in the Arctic conditions, it is more preferable to use thermal insulating materials with mineral components (Table 1).

Table 1. Comparison of the characteristics of different types of insulation wool.

Name of Parameters	Slag Wool	Glass Wool	TBF	STBF
Limit temperature application, °C	up to 250	from −60 to +450	from −190 to +700	from −190 to +1000
Sintering temperature, °C	250–300	450–500	700–1000	1100–1500
Average fiber diameter, µm	4 to 12	4 to 12	5 to 15	1 to 3
Length of fibers, mm	16	15–50	20–50	50–70
Sorption humidification per 24 h. (max), %	1.9	1.7	0.035	0.02
Using the binder	yes	yes	yes	no
Presence of binder, %	2.5 to 10	2.5 to 10	2.5 to 10	-
Thermal conductivity coefficient, W/(m·K)	0.46–0.48	0.038–0.046	0.038–0.046	0.035–0.046
Heat capacity, J/kg·K	1000	1050	500–800	800–1000
Density, kg/m ³	75–400	10–130	26–36	18–25
Sound absorption coefficient	0.75 to 0.82	0.8 to 92	0.8 to 95	0.95 to 99
Vibration resistance	no	no	no	yes

Consider the products of structural fire protection on the basis of STBF of two Russian manufacturers LLC “PROMIZOL” and LLC “BST” and international company “3M”. All these flame retardant coatings belong to KM0 class [34] and are complex composites in the form of bendable sheets (rolls). “PROMISOL-MIKS PROPLATE-50-K” and “BST-MAT” consist of a combination of noncombustible materials from STBF, glass wool, silica fabrics, and attachment straps on their bases, while “3M Interam” represents a flexible mat with basalt fiber and endothermic components, including a fireproof waterproof sealant, aluminum tape, and steel tape bandage. The main advantages of the considered fire-retardant coatings are: “dry” installation on various steel structures of buildings and constructions, corrosion resistance, easiness of installation on structures of complex shape, and the possibility of long-term operation in severe conditions.

The purpose of this article is to study structural protection on the basis of STBF under operating conditions in the Arctic climate. Fire retardant materials “PROMISOL-MIX PROPLEIT-50-K” (sample No. 1) and “BST-MAT” (sample No. 2) during fire test under a hydrocarbon temperature regime and fire retardant “3M Interam” (sample No. 3.1 and sample No. 3.2) during cryogenic exposure and during a subsequent fire test under a hydrocarbon fire regime were considered.

2. Materials and Methods

Experimental samples were tested according to [35,36] under the condition of creating a hydrocarbon temperature regime in the fire chamber of the furnace according to [10], characterized by the following dependence (1):

$$T - T_0 = 1080 \cdot \left(1 - 0.325 \cdot e^{-0.167t} - 0.675 \cdot e^{-2.5t} \right) \quad (1)$$

where T means the temperature inside the furnace in °C, corresponding to the relevant time t ; T_0 is the temperature in °C inside the furnace prior to the start of heat impact; and t is the time in min from the start of the test.

The limiting state during fire testing under the hydrocarbon temperature regime is assumed to be when the metal of the test sample reaches the critical temperature equal to 500 °C. The conditions of cryogenic tests were established according to [5–7], and the conditions of fire tests were established according to [35].

The humidity of the fire retardant was dynamically balanced with the environment with a relative humidity of $(60 \pm 15)\%$ at a temperature of (20 ± 10) °C.

For samples No. 1 and No. 2, the temperature in the furnace's firing chamber was measured by thermocouples, installed by caulking in the amount of three pieces in the average cross-section of the samples on the I-beam wall and on the inner surface of the flanges in accordance with [36], and for samples No. 3.1 and No. 3.2 six thermocouples were installed, three main and three duplicating, symmetrically to the main.

2.1. Experiment No. 1

Sample No. 1 was a steel column of I-shaped cross-section No. 20B1 [37] with a height of 1700 mm and a section ratio of 294 mm^{-1} [38]. The thickness of the protective layer on the prototype was 50 mm. The test was carried out in the VNIPO of the Ministry of Emergency Situations in Russia.

Sample No. 1 was placed in the fire chamber of the furnace and subjected to four-sided heat exposure without static load until the limit state of the sample. The temperature in the fire chamber was created by the hydrocarbon fire regime according to (1) and was measured with furnace thermocouples in five locations.

2.2. Experiment No. 2

Sample No. 2 was a steel column of I-shaped cross-section No. 50B2 [37] with a height of 1700 mm and a section ratio of 172 mm^{-1} [38]. The thickness of the protective layer on the prototype was 20 mm. The test was carried out in the testing laboratory «POZH-AUDIT».

Before the tests, measurements were made of the actual thickness of the fire-retardant coating applied to the sample. The thickness of the coating was measured at 36 points along the perimeter of the heated surface, in steps of 500 mm along the height of the sample.

Sample No. 2 was placed in the fire chamber of the furnace and subjected to four-sided heat exposure without static load. In the fire chamber of the furnace, a hydrocarbon temperature regime was created according to (1).

2.3. Experiment No. 3

Two samples were examined for the experiment No. 3. Sample No. 3.1 was a steel column of I-shaped cross-section No. 50B2 [37] with a section ratio of 170 mm^{-1} [38], with flame-retardant coating with the following composition: endothermic 3M Interam® E-Mat® in 2 layers with a total thickness of 20.6 mm, waterproof flame retardant sealant 3M 3000WT, 3M Aluminum tape 425/437 and steel tape bandage. Sample No. 3.2 was a steel column of I-shaped cross-section No. 50B2 [37] with a section ratio of 170 mm^{-1} [38] and flame-retardant coating of the following composition: endothermic 3M Interam® E-Mat® in 3 layers with a total thickness of 30.9 mm, waterproof flame retardant sealant 3M 3000WT, 3M Aluminum tape 425/437, and steel tape bandage. The test was conducted at the test center «Ognestoykost».

The tests of the samples were carried out in two stages: the stage of cryogenic exposure and the stage of thermal exposure under hydrocarbon fire conditions according to (1). Both test stages were conducted sequentially on the same day.

Test methods for the different character of cryogenic liquid hydrocarbon emissions are assigned in the ISO 20088 series of standards [5–7], where liquid nitrogen is used as a liquid hydrocarbon analogue, since it has a lower boiling point than LNG or liquid oxygen and is not flammable.

ISO 20088-1 [5] includes complete immersion of the test sample in a cryogenic liquid. The limiting temperature drop is defined as the difference between the ambient temperature and the limiting temperature for the steel. The sample meets the requirements provided that the temperature does not exceed the limit temperature.

The test to determine the time of reaching the critical state under cryogenic exposure was carried out according to the regulations of ISO 20088-1 [5] with a decrease in the limiting temperature to $-50\text{ }^{\circ}\text{C}$ as requested by the technical customer. The duration of exposure to liquid nitrogen on the flame retardant system was 60 min. After the specified time, the cryogenic exposure of the flame retardant sample was stopped.

To conduct the cryogenic test, a tank made of polystyrene foam with dimensions of at least $700\text{ mm} \times 180\text{ mm} \times 80\text{ mm}$ (Figure 2) was glued to the surface of the fireproof mat strictly in the center of the I-beam flange using a flame-retardant sealant. The area of the tank overlapped the attachment points of thermocouples on the beam flange. Then, at least 3.5 L of liquid nitrogen was poured into the tank, and to reduce the rate of vaporization, the tank was covered with a sheet of polystyrene foam 50 mm thick from above.

Figure 2. (a) Schematic diagram of the fire protection coating assembly; (b) Section of the fire protection coating assembly with thermocouple location.

After the end of exposure to liquid nitrogen on the flame retardant systems of samples No. 3.1 and No. 3.2, a tank of polystyrene foam and sealant residues were removed from its surface. After these measures, to conduct fire tests, the samples were placed in a test furnace, in which a hydrocarbon temperature regime was maintained, characterized by dependence (1).

3. Results

3.1. The Results of Experiment No. 1

According to the test results it was found that sample No. 1 of 50 mm thickness provides fire protection efficiency under conditions of exposure to hydrocarbon combustion regime for 90 min for steel column of I-beam section of profile No.20B1 of 1700 mm height with a section ratio of 294 mm^{-1} . During the tests, no visible changes in the external state of the sample were recorded: there were no cracks, fissures, damage, or charring of the surface, and there was no smoke emission (Figure 3). Belts and steel straps were not subjected to changes. The experiment was stopped at 95 min after reaching the critical temperature on the sample. As a critical temperature, $500\text{ }^{\circ}\text{C}$ is taken, the average value of measurements of thermocouples, installed by caulking in the amount of three pieces in the average cross-section of the samples on the I-beam wall and on the inner surface of the flanges.

Figure 3. (a) Sample No. 1 before the test; (b) during the test; (c) after the test.

3.2. The Results of Experiment No. 2

According to the test results, it was found that sample No. 2 of 20 mm thickness provides fire protection efficiency under conditions of exposure to a hydrocarbon combustion regime for 90 min for steel column of I-beam section of profile No.50B2 of 1700 mm height with a section ratio of 172 mm^{-1} . At the end of the experiment, burning of aluminum foil and slight embrittlement were observed on the surface. The steel ties did not present any changes. The experiment was stopped at 92 min after reaching the critical temperature on the sample (Figure 4).

Figure 4. (a) Sample No. 2 before the test; (b) after the test.

3.3. The Results of Experiment No. 3

According to the test results, sample No. 3.1 of 20.6 mm dry layer thickness applied to a steel column of the I-beam section of profile No.50B2 with a section ratio of 170 mm^{-1} provides a time of reaching the critical temperature $-50 \text{ }^{\circ}\text{C}$ in the sample during 60 min in the mode of cryogenic influence of liquid nitrogen vapor, and a subsequent time of reaching critical temperature $500 \text{ }^{\circ}\text{C}$ in the sample during 90 min in the hydrocarbon combustion mode.

According to the test results, sample No. 3.2 of 30.9 mm dry layer thickness applied to a steel column of the I-beam section of profile No.50B2 with a section ratio of 170 mm^{-1} provides a time of reaching critical temperature $-50 \text{ }^{\circ}\text{C}$ in the sample during 60 min in the mode of cryogenic influence of liquid nitrogen vapor, and a subsequent time of reaching

critical temperature 500 °C in the sample during 90 min in the hydrocarbon combustion mode.

Cryogenic test on the flame retardant systems of samples No. 3.1 and No. 3.2 showed that 1 h exposure to liquid nitrogen does not significantly reduce the surface temperature of the protected metal. In the case of the two-layer system (sample No. 3.1), the temperature decreases by 10–15 °C from the initial temperature. In the case of the three-layer system (sample No. 3.2), no change in the temperature of the metal was recorded. Immediately after the complete evaporation of liquid nitrogen from the surface of the samples, at least 10 hammer blows were made, as a result of which the fire-retardant systems did not crack, split, or delaminate (Figure 5).

Figure 5. (a) Samples No. 3.1 and No. 3.2 during fire tests; (b) after all tests.

4. Discussion

Sample No. 3.1 with a dry layer thickness of 20.6 mm and a section ratio of 170 mm^{−1} after cryogenic testing for 60 min provides similar fire protection efficiency as the coating of sample No. 1 with a thickness of 50 mm and a section ratio of 294 mm^{−1} and sample No. 2 with a thickness of 20 mm and a section ratio of 172 mm^{−1}, subjected to conditions of the hydrocarbon burning regime without cryogenic influence (Table 2). Sample No. 3.2 with a dry layer thickness of 30.9 mm after cryogenic testing for 60 min provides a time of reaching a critical temperature of +500 °C in the sample for at least 120 min.

Table 2. Comparison of initial data and obtained results of fire retardant coatings based on STBF.

Parameters/Names of Flame Retardant Coatings	Sample No. 1	Sample No. 2	Sample No. 3.1/Sample No. 3.2
Tested samples	I-section column No.20B1	I-section column No.50B2	I-section column No.50B2
A_p/V , mm ^{−1}	294	172	170
Thickness of dry layer of fire retardant, mm	50	20	20.6/30.9
Presence of cryogenic test	no	no	yes
Cryogenic test time, min	-	-	60 (without reaching critical temperature)
Moment of the start of the fire test	as the sample is ready and the furnace is prepared	as the sample is ready and the furnace is prepared	2.5 h after cryogenic test
Fire regime	hydrocarbon	hydrocarbon	hydrocarbon
Fire protection efficiency	90	90	90/147

Fire tests of the experimental samples were conducted in accordance with [35,36] under the condition of creating a hydrocarbon temperature regime in the furnace according to [10], thereby by the plotted graphs we can say about the character of the curve growth (Figure 6).

Figure 6. Temperature changes on the samples during the fire test.

In the process of fire testing the flame retardant coating of sample No. 1, a smooth increase in temperature is observed during the first minutes of the test with a subsequent “linear” increase practically during all phases of the test, while with sample No. 3.2 with material thickness 30.9 mm during the first 12 min, there was almost no temperature change. Moreover, with sample No. 3.1 with material thickness 20.6 mm during 21 min, as the heat absorption process takes place, then a faster heating begins, as a result of which the given fire protection product approaches samples No. 1 and 2 for 90 min.

Since the tests were conducted on columns with different section ratios, a direct comparison according to Figure 6 will not be quite correct. Let’s consider a diagram of multifactor analysis of these flame retardants as a function of technological, operational, and cost parameters, and express these dependencies as histograms (Figure 7). The following parameters were taken into account: fire protection efficiency at hydrocarbon and standard temperature conditions (R90 HC, R90), frost resistance, structural load, service life over 25 years, corrosion resistance, vibration resistance, adhesion to the substrate, resistance to weather conditions, maintainability, and cost. Let’s assume that the evaluation of fire protection means will be expressed in relative units (points) from 1 (low score) to 5 (high score).

So, structural protection with an endothermic effect presents the best rates of fire protection efficiency and does not concede other indicators of structural fire protection based on STBF, but at the same time it is significantly more expensive than its counterparts. Since the fire protection products considered in this article are planned to operate in the conditions of the Arctic and Antarctic, it is obvious that plaster compositions and epoxy coatings, as materials of a “wet process”, are not suitable for such tasks. In turn, epoxy coatings are not non-combustible materials, unlike plaster compositions and structural protection.

Figure 7. (a) Diagram and (b) histograms for different types of fire protection (red—epoxy coatings, green—structural protection on STBF, yellow—plaster compositions and gray—structural protection endothermic).

5. Conclusions

Nowadays, in connection with the expansion of the world oil and gas industry in the Arctic and Antarctic, the problem with the protection of steel structures of buildings under hydrocarbon fire conditions, including after cryogenic spillage of liquefied hydrocarbons, is apparent. Over the past five years, the design of steel structures with increased fire resistance limits has been regulated by international and industry standards of oil and gas facilities, which impose requirements on fire protection means for steel structures in terms of resistance to cryogenic effects of cryogenic liquids and tests under a hydrocarbon fire regime. There are not many studies devoted to this topic due to its relative novelty. Developments in the field of fire protection of steel structures under arctic climate conditions are expected.

According to the results of the study, the most effective means of fire protection of steel structures in the Arctic and Antarctic are materials based on STBF, providing a “dry” method of installation, long operating time in severe conditions, resistance to the cryogenic spillage of liquefied hydrocarbons and a hydrocarbon fire regime.

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