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PARAMETERS OF FIRE-RETARDANT COATINGS OF STEEL CONSTRUCTIONS UNDER THE INFLUENCE OF CLIMATIC FACTORS

Purpose. To assess an influence of climatic factors on properties of the reactive flame retardant coating "FENYKS STS" for analyzing steel building structures fire resistance for their use in coal mining.

Methodology. Scientific generalization and systematization, analysis of regulatory requirements for building structures fire resistance. Experimental study methods regarding the reaction of samples to heating, regulated by the regulations about fire protection DSTU–N–P B V.1.1–29:2010. Fireproofing of building constructions and general requirements and control methods. Mathematical and computer simulation of non-stationary heat exchange processes in "steel plate – fire protection coating" system. Definition of thermophysical properties and protection ability of fire protection coatings based on solving direct and inverse heat conduction problems.

Findings. Based on developed two-layered physical and simulation models of fire protected steel plate, there was determined a coefficient of thermal conductivity of the "FENYKS STS" coating, which depends on temperature. The stable volumetric heat capacity has been defined. The efficiency of this coating for the protection of metal constructions has been proved. The influence of climatic factors on thermophysical properties of the coating and its fire protection ability is shown.

Originality. For the first time, the value of thermal conductivity for the "FENYKS STS" coating was determined after the influence of climatic factors during 3 years. The conclusion is that the fire protection ability of this coating does not change during that time.

Practical value. The results will allow making more accurate estimation related to fire resistance of fire protected steel constructions for a long-term use. The studies will be useful for designers and fire-retardant manufacturers, since they will allow calculating an effective fire-resistance thicknesses of the covering taking into consideration its time of use.

Keywords: *flame-retardant coating, fire-retardant ability, thermophysical properties*

Introduction. Fixing supports of mine workings is the most difficult and time-consuming process in underground coal deposits mining. Despite the widespread use of steel frame fastenings made of heavy special profiles (in more than 80 % of mine workings), the annual reinforcement is more than 10 % of the total length of supported workings. About 15 % of the total number of underground workers is employed in repair work. Nowadays, between 30 to 50 % of mines in Ukraine are considered to be dangerous for people. Unsatisfactory condition of construction fastening is one of the main causes of high injury to miners.

Variety of mining and geological conditions and search for the cost-effective solutions have led to invention of a large number of types of lagging (more than 30), most of which have not found industrial use. In the preparatory workings of coal mines, generally, there are used bearing structures of lagging, which can be rigid (reinforced concrete structures), semi-elastic (steel, wooden, polymeric tightening) and elastic (metal mesh, roll glass fiber, etc.).

At the same time, as shown by the long experience of using steel frame fastenings in complex mining-geological conditions, they have a number of significant disadvantages.

In the Donbass, the transition of mining operations from a depth of 500 to 1000 m caused increase in rock displacement in preparatory excavations by almost 3 times, with the mounting pressure increase to 200 kPa. Despite the high material capacity of frame supports, 30–50 % of them are deformed, and about 20 % are in an unsatisfactory condition.

The majority of such steel structures have fire resistance level which does not meet the normative documents requirements.

There are three methods to raise the fire resistance of such structures to a level that meets the regulatory requirements:

- fire protection of constructions;
- use of fire-resistant steels;
- application of external bearing structures.

Fire protection blocks the heat flow from fire toward the construction surface and protects it from fast warming. This allows maintaining the load bearing capacity of construction for a certain time. Steel structures have high thermal conductivity. Therefore, the fire protection is based on creation of heat-insulating screens on the surface of the steel elements that withstand the influence of fire or high temperatures. The fire resistance of building structures depends on the thermophysical properties of fire protection compositions. They are used to increase the fire resistance of such structures by creating a porous heat-insulating layer on the protected surface.

Another important factor that can affect the properties of fire protection coatings, during its use under different conditions, involves climatic factors (humidity, temperature). Research on the influence of these parameters will allow determining with high accuracy the dependence of the minimum thickness of flame retardant coating on thickness of the metal for the normalized values of the steel structure fire resistance [1].

According to fire statistics, most of the buildings where fires occurred had a third degree of fire resistance. Accordingly, there is a need to develop fire protection projects for building structures to ensure the required degree of their resistance.

Functional use of reconstructed buildings may also change, as a result, the fire safety requirements of those objects increase.

The use of steel constructions that were produced without regard to the requirements of fire resistance, can lead to human casualties, significant damage and environmental pollution [2, 3]. The problem of the safety of constructions, the prediction of behavior in emergencies and in before-emergency situations is very relevant [4].

Literature review. At present, there is no document in Ukraine that would require such research. In foreign publications, in particular, [5] describes the impact of marine climate on the fire protection coatings during field tests. However, there is no data about fire tests for such coatings after exposure. In papers [6, 7], data is given on accelerated climatic tests. For the determination of flame-retardant efficiency, the intumescent coating coefficient was used, which does not fully describe the flame retardant effectiveness of the coating. It is also proposed in [6] to take into account such a coefficient as the adhesion of the coating to the protected surface. In [8], there was made an assessment about keeping the fire protection features of coatings for metallic structures before and after accelerated climatic tests during certification tests. In the Republic of Belarus, there are regulations about methods that determine the resistance of coatings depending on its aging for fire protection of metal. As the main indicators there is used a fire protection efficiency and adhesion [7]. The work [9, 10] is devoted to testing of building structures fire resistance. Another study [11] describes the analysis of hydrocarbons fires. The next articles [12, 13] do not contain data about determination of fire resistance coatings for metal structures after the fire influence. According to the analysis, the mentioned works do not fully describe the issue of determining the parameters of fire protective coatings of steel structures after affecting their climatic factors. These parameters include thermophysical properties and characteristics of the fire protection capability of the coating according to the known method. Therefore, a study on the influence of climatic factors on the fire protection coatings for steel structures will allow providing more accurate approach in case of assessing the fire resistance of steel structures which are protected by fire retardant coatings, with long-term operation both in heating and non-heated premises [14].

Purpose. The aim of the work is to study the influence of climatic factors on the properties of the reactive flame retardant coating "FENYKS STS" for analyzing the fire resistance of steel building structures for their use in development of coal deposits.

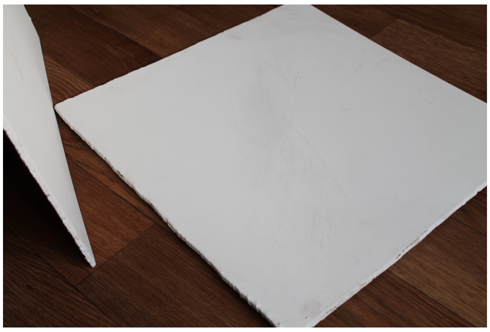
To achieve the aim of this study it is necessary to solve the following tasks:

- to conduct accelerated climatic tests on samples of steel structures protected by reactive coating "FENYKS STS";
- to experimentally research the fire protection parameters of steel structures samples in standard temperature conditions;
- to substantiate parameters of the fire protection cover for the protection of steel structures after the influence of climatic factors on it.

Methods. In order to determine the thermophysical properties of the investigated fire retardant coating, there were used calculation-experimental methods. Thus, we can determine the required characteristics of the object.

In order to make the fire studies, there were used four steel plates made of steel St. 3 (Fig. 1, *a*), the size of 500·500 mm and 5 mm thickness, with a fire-retardant agent deposited on one surface of the plate. On the heating surface of a steel plate there was put a layer of soil GF-021 before the fire-retardant agent application, thickness of 0.065 mm.

a



b

Fig. 1. Appearance of the steel samples:

a – before the fire-retardant agent application; b – after the fire-retardant agent application

The fire-retardant agent was applied according to the manufacturer's technology for a specific surface, adhere to all the requirements, including the application of soil (Fig. 1, *b*) [15]. The substance was applied mechanically by an airless spray unit in accordance with the regulations of work on fire protection. Two out of four steel plates were control samples; they were not exposed to climatic factors.

In order to measure the thickness of the formed fire protection coating, there was used a thickness gauge. This device measured 9 points, whose average thickness was 0.31 mm.

The determination of the fire protection coating parameters after the climatic factors impact on it were carried out in 2 stages. At the first stage there was accelerated artificial aging of steel plates with a fire-retardant coating in a climate chamber BINDER KBF 240. The second stage consisted of fire tests of coated steel plates after holding them in the climatic chamber and comparison of data with control samples.

The climate control chamber BINDER KBF 240 allows conducting a research study in the temperature range: –10 – +60 °C and humidity from 0 to 100 %. (Fig. 2).

The essence of climatic tests consisted in the cyclic reproduction of temperature and humidity schedule in the chamber according to the appropriate method. During the tests there are eight repetitions of this cycle, which is relevant to 1 year of fire protection coverage in real climatic conditions.

As a result of the first stage procedure which consisted of the artificial aging of the steel plates with a fire-

Fig. 2. General appearance of the climate camera BINDER KBF 240

retardant coating in the climatic chamber BINDER KBF 240, there were created obsolete samples (1 and 3 years accordingly). During the process of accelerated aging, there was no significant "flushing" of the fire-retardant coating from the surface of the investigated steel plate. However, visible changes during the visual inspection were not detected.

During the next step there were conducted fire tests on the coated steel plates after an exposure in the climatic chamber. Furthermore, the data was compared with the control samples according to the method [16].

In order to measure the temperature from the unheated surface of the steel plate, there were three thermocouples of the TCA type (Fig. 3) with a diameter of wire 0.5 mm (T1-T3), one thermocouple (T2) in the center of the sample and two (T1, T3) at a distance of 100 mm from the edges of the plate. The seams of thermocouples are rolled into metal at a depth of 2 mm and are fixed with a thermal insulating material.

From the non-heating surface, the plate was protected by two layers of thermal insulation material felt, 20 mm thick, and a plate of mineral wool with density of 75 kg/m^3 and a thickness of 50 mm (Fig. 4).

The tests were conducted at a temperature of 15.8 °C, relative humidity of 48 % and pressure of 743 mm/Hg.

The essence of the test was to create a temperature regime in the furnace, which is relevant to the standard fire temperature regime thanks to the burning of liquid fuel (Fig. 5). After the beginning of the test and before its end, the excess pressure in the furnace was 10 Pa.

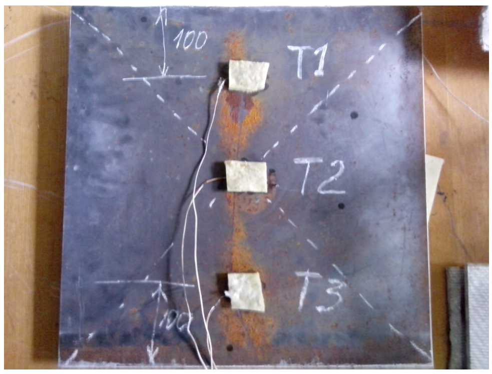


Fig. 3. Scheme of the thermocouple placement from an unheated surface of the steel plate before the test

Fig. 4. View of the test sample from the non-heating surface of the steel plate

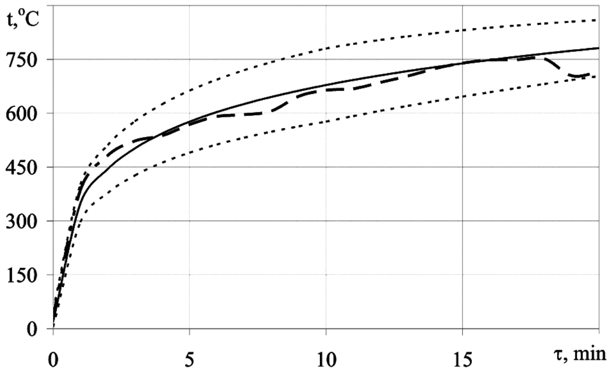


Fig. 5. Dependence of the temperature in furnace on the duration of fire influence:

—— – standard temperature curve of fire according to State Standards of Ukraine B V 1.1-4 [13]; .... – maximum (upper curve) and minimum (lower curve) acceptable values of the temperature in the furnace during the tests; ·—·–– – real curve of temperature changes in the furnace

During the test, the experimental specimen was subjected to the thermal action. Also the time was determined from the beginning of the action until the temperature of 550 °C reached the non-heating surface of the steel plate [17, 18].

The temperature from the non-heating surface during this 17-minute test reached a critical temperature for the steel plate (550 °C) (Fig. 6).

Subsequently, in order to indicate the thermophysical properties of the coating, the indicator's average values of the three thermocouples were used (Fig. 6).

The results of the investigation are presented as an example of sample No. 1 below.

Results of the investigations. As we can see from Fig. 6, the character of the curves dependence of the temperature of non-heating surface of a steel plate coincides with the time of fire exposure. It shows that the plate is uniformly warmed up in different parts of the

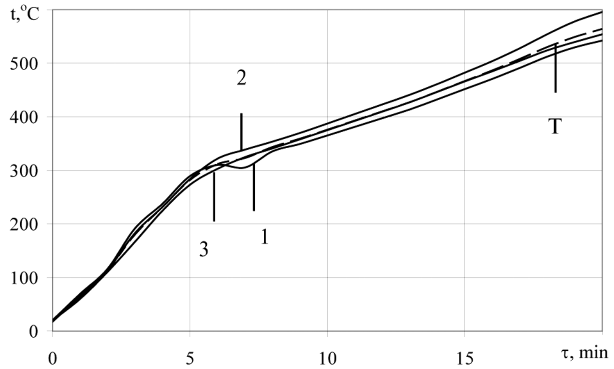


Fig. 6. Temperature dependence of the non-heating surface of the steel plate of sample No. 1 on the time of fire exposure at different points of temperature measurement:

1 – thermocouple, installed at a distance of 100 mm from the upper edge of the plate; 2 – thermocouple, installed in the center of the plate; 3 – thermocouple, installed at a distance of 100 mm from the bottom edge of the plate; T – the middling values of the three thermocouples

temperature measurement, and the differences in the observed heating rate are explained by the heterogeneity of the flame retardant coating thickness.

After the tests, during the visual inspection of the samples it was revealed that:

- an extinguishing agent "FENYKS STS", which was applied on the steel plate with the size of 500 · 500 ·5 mm with a primer of GF-021 (thickness of 0.065 mm), has a sufficient adhesion strength;
- there were no detachments of the formed coating from the steel plate over the area;
- the average thickness of the intumescent layer after the test was 12 mm (8–16 mm).

In order to determine the characteristics of the fire resistance coatings of the steel structures using the calculation-experimental method, the most adequate physical and mathematical models of thermal processes occurring in such system during testing were used.

The physical model is described by a system consisting of two layers: a steel plate, with a thickness of 5 mm (δ_1) and a fire retardant coating (δ_2), 0.31 mm thick (Fig. 7).

The total thickness of the system is the sum of the thicknesses of individual layers. During the testing, the right surface of the plate is heated by the convective-radiation mechanisms of heat transfer from the hot gases in the furnace with the temperature Tm1, which is close to the standard fire curve, and the heat transfer coefficient α_{c2} = 25 W/m^2 · K. The left surface of the plate is cooled by the convection in the environment with the temperature T_{m2} = 15.8 °C, the heat transfer coefficient from the unheated surface α_{c2} is taken at 5 W/(m^2 · K).

Inside the ceiling, heat is transmitted only by the thermal conductivity. The conditions of the ideal thermal contact between the separate layers of the plate are accepted.

The heat transfer coefficient of the steel plate was assumed to be 45 W/(m · K), and the specific volumetric

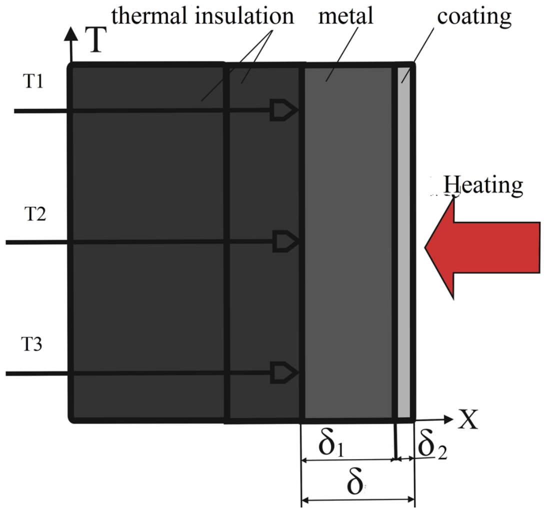


Fig. 7. Physical model of a steel plate with a fire protection coating in one-dimensional formulation

heat capacity was $4 \cdot 10^6$ J/($m^3 \cdot$ K). There were 15 nodes of the numerical model, in spatial coordinate with a step time of 30 seconds.

Since the investigated coating is reactive, it means that it expands (with the possibility of increasing the initial thickness increase of the coating up to 100 times), therefore, the principle of the increasing of the initial thickness coating during the heating is not known. The logical question arises, to which thickness we should refer the received coefficients of the effective heat conductivity and the specific volumetric heat capacity.

In this investigation it has been assumed that the obtained coefficients of the effective heat conductivity and the specific volumetric heat capacity of the coating are related to the initial thickness of the coating. Therefore, the calculation models of the process of thermal conductivity with the coatings were also taken with the thicknesses of coatings that do not change over time.

The mathematical model of the process of heat conductivity in a two-layer system in the Cartesian coordinate system, which describes the above physical model, is repeatedly described in the literature [19]. It represents a one-dimensional heat conduction equation with a combination of radiant heat transfer and boundary conditions of the 3rd kind on the heating and non-heating surfaces, and also takes into account the ambient temperature.

Discussion. The obtained data (temperatures from the unheated surface of a steel plate) were used in solving the inverse heat conduction problems. As a result of the calculations, the thermophysical properties of the fire protection coating were determined: the dependence of the coefficient of the thermal conductivity on the temperature (Fig. 8) and the constant value of the specific volume heat capacity $1 \cdot 10^5$ J/m^3. The inverse problem of thermal conductivity was solved by an extremal method based on the use of the iterative Newton-Gauss algorithm for finding the minimum of the function *F* and Tikhonov A. M. regularization method [19].

The curve for the obtained dependence of the coefficient of thermal conductivity of the fire retardant coat-

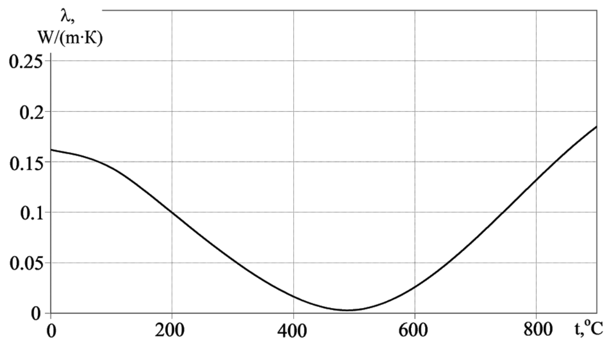


Fig. 8. Dependence of the effective coefficient of thermal conductivity of the "Phoenix STS" coating on the temperature found by the solution of the inverse heat conduction problem

ing "FENYKS STS" on temperature can be explained as follows (Fig. 8). The curve of the coefficient of thermal conductivity from the initial temperature to 500 °C linearly decreases. This is explained by the flaking of the coating and the tenfold increase in thickness in relation to the initial thickness. Linear growth after 500 °C is due to an increase in the radiation component of the thermal conductivity coefficient and its conductive component (due to shrinkage (sintering) of the coke layer and its partial destruction).

Using the found TPC coatings by solving a series of direct heat conduction problems, we determine the dependence of the minimum thickness of the study coating on the thickness of the steel plate, the normalized duration of fire exposure and the critical temperature of the steel.

Comparing the obtained thermophysical properties of the coating with the ones defined, it becomes obvious that defining the characteristics of the fire retardant capability of the "FENYKS STS" coating is inappropriate. From the comparison, it becomes clear that the thermophysical properties will not affect the value of the minimum thickness of the "FENYKS STS" coating on the thickness of the steel plate, the normalized duration of fire exposure and the critical temperature of the steel.

Therefore, the further research will be aimed at increasing the time of the impact of climatic factors by accelerating the artificial aging of steel plates with a fire-retardant coating in a climate chamber BINDER KBF 240. Studies have shown that the effect, which is equal to 3 years of operation, does not affect the thermophysical properties of the coating, and therefore also does not affect the fire protection ability. This is a promising direction for the further research in this field.

The advantage of the proposed method is the ability to determine the parameters of fire retardant coatings at much shorter time than real-time natural climatic tests. These results will allow estimating the fire resistances of steel constructions with fire protection at long-term use more accurately. The studies will be useful for designers, manufacturers of fire retardants. They will allow calculating the thicknesses of coatings that would provide the normalized fire resistance limit of the construction taking into account the time of use.

This work is a continuation of the series of work about increasing the fire resistance of steel structures protected by the fire retardant coatings. However, with taking into account the influence of climatic factors on it, which will make it possible to expand the scope of coatings taking into account the use time [20].

Conclusions.

1. The tests were conducted of steel plate with dimensions of 500 · 500 · 5 mm. One side of the plate was covered by the flame retardant intumescent covering "FENYKS STS", with an average thickness of 0.31 mm under the conditions of heating in a fire furnace with the standard fire conditions temperature after the impact of climatic factors on the coverage, which is equivalent to the operation of the coating for a period of 3 years.

2. There were developed two-layer physical and simulation models of a steel plate with fireproof coating. With its help, the coefficient of thermal conductivity of the "FENYKS STS" fire retardant coating, which is temperature dependent, was determined. The constant specific volumetric heat capacity was determined and the efficiency of this coating for protection of metal constructions was proved. It was found that the curve of the coefficient of thermal conductivity from the initial temperature to 500 °C linearly decreases. It can be explained by the intumescent of the coating and the increase in thickness by dozens of times in relation to the original thickness. The linear growth after 500 °C is due to an increase in the radiation component of the thermal conductivity coefficient and its conductive component (due to shrinkage (sintering) of the coke layer and its partial destruction).

3. It was established that the value of the coefficient of the thermal conductivity of the "FENYKS STS" coating, which was found after the influence of climatic factors during 3 years, is similar to the value of this coefficient without influence. It is concluded that the fire protection ability of coating does not change during this time. The direction of further research is to increase the time of climatic influence (up to 10 years) by using the proposed methodology and the fire tests of steel plates with flame retardant coatings after the influence.

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Параметри вогнезахисних покриттів сталевих конструкцій після впливу кліматичних факторів

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Мета. Оцінити вплив кліматичних факторів на властивості реактивного вогнезахисного покриття „Фенікс СТС“ для аналізу вогнестійкості сталевих будівельних конструкцій з використанням їх при розробці вугільних родовищ.

Методика. Наукове узагальнення й систематизація, аналіз вимог нормативних документів щодо вогнестійкості будівельних конструкцій, методи експериментального дослідження поведінки зразків при нагріванні, регламентованих вимогами ДСТУ–Н–П Б В.1.1–29:2010 „Захист від пожежі. Вогнезахисне обробляння будівельних конструкцій. Загальні вимоги та методи контролю“. Математичне та комп'ютерне моделювання процесів нестаціонарного теплообміну в системі „сталева пластина – вогнезахисне покриття“. Визначення теплофізичних характеристик і характеристики вогнезахисної здатності вогнезахисних покриттів на основі розв'язання прямих і обернених задач теплопровідності.

Результати. На основі розробленої двошарової фізичної та імітаційної моделі сталевої пластини з вогнезахисним покриттям визначено коефіцієнт теплопровідності вогнезахисного покриття „Фенікс СТС“, що залежить від температури. Визначена постійна питома об'ємна теплоємність і доведена ефективність цього покриття для захисту металевих конструкцій. Показано вплив кліматичних факторів на теплофізичні характеристики покриття та на його вогнезахисну здатність.

Наукова новизна. Уперше визначене значення коефіцієнту теплопровідності покриття „Фенікс СТС“, знайденого після впливу кліматичних факторів протягом 3 років. Зроблено висновок, що вогнезахисна здатність покриття не змінюється протягом цього часу.

Практична значимість. Наведені результати дозволять із більшою точністю підходити до оцінювання вогнестійкості сталевих конструкцій із вогнезахистом при тривалому використанні. Дослідження будуть корисними для проектувальників, виробників вогнезахисних речовин, так як дадуть змогу розраховувати таку товщину покриттів, що буде забезпечувати нормовану межу вогнестійкості конструкції з урахуванням часу використання.

Ключові слова: *вогнезахисне покриття, вогнезахисна здатність, теплофізичні характеристики*

Параметры огнезащитных покрытий стальных конструкций после воздействия климатических факторов

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Цель. Оценить влияние климатических факторов на свойства реактивного огнезащитного покрытия „Феникс СТС“ для анализа огнестойкости стальных строительных конструкций с использованием их при разработке угольных месторождений.

Методика. Научное обобщение и систематизация, анализ требований нормативных документов по огнестойкости строительных конструкций, методы экспериментального исследования поведения образцов при нагревании, регламентированных требованиями ДСТУ-Н-П Б В.1.1-29: 2010 „Защита от пожара. Огнезащитная обработка строительных конструкций. Общие требования и методы контроля“. Математическое и компьютерное моделирование процессов нестационарного теплообмена в системе „стальная пластина – огнезащитное покрытие“. Определение теплофизических характеристик и характеристики огнезащитной способности огнезащитных покрытий на основе решения прямых и обратных задач теплопроводности.

Результаты. На основе разработанной двухслойный физической и имитационной модели стальной пластины с огнезащитным покрытием определен коэффициент теплопроводности огнезащитного покрытия „Феникс СТС“, который зависит от температуры. Определена постоянная удельная объемная теплоемкость и доказана эффективность этого покрытия для защиты металлических конструкций. Показано влияние климатических факторов на теплофизические характеристики покрытия и на его огнезащитную способность.

Научная новизна. Впервые определены значения коэффициента теплопроводности покрытия „Феникс СТС“, найденного после воздействия климатических факторов в течение 3 лет. Сделан вывод, что огнезащитная способность покрытия не меняется в течение этого времени.

Практическая значимость. Приведенные результаты позволят с большей точностью подходить к оценке огнестойкости стальных конструкций с огнезащитой при длительном использовании. Исследования будут полезными для проектировщиков, производителей огнезащитных веществ, так как позволят рассчитывать такую толщину покрытий, которая будет обеспечивать нормированный предел огнестийкости конструкции с учетом времени использования.

Ключевые слова: *огнезащитное покрытие, огнезащитная способность, теплофизические характеристики*

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