UDC 614.842
DOI: 10.15587/1729-4061.2023.275550

DETERMINING THE THERMAL-PHYSICAL CHARACTERISTICS OF A COKE FOAM LAYER IN THE FIRE PROTECTION OF CABLE ARTICLES WITH FOAMING COATING

Yuriy Tsapko
Corresponding author
Doctor of Technical Sciences, Professor*
Department of Technology and Design of Wood Products
National University of Life and Environmental Sciences of Ukraine
Heroiv Oborony str., 15, Kyiv, Ukraine, 03041
E-mail: juriyts@ukr.net

Ruslan Likhnyovskyi
PhD
Research and Testing Center***

Aleksii Tsapko
PhD, Senior Research Fellow*
Department of Research of Quality and Conditions of Storage of Oil Products and Industrial Group of Goods
Ukrainian State Research Institute "Resurs"
Kasimir Malevich str., 84, Kyiv, Ukraine, 03150

Vitalii Kovalenko
PhD***

Oksana Slutska
PhD
Research Center for Civil Protection***

Pavlo Illiuchenko
Research and Testing Center***

Rostyslav Kravchenko
PhD
Research Center of Fire Protection***

Maryna Sukhanevych
Doctor of Technical Sciences, Associate Professor
Department of Building Materials**
*V. D. Glukhovsky Scientific Research Institute for Binders and Materials**
**Kyiv National University of Construction and Architecture
Povitroflotsky ave., 31, Kyiv, Ukraine, 03037
***Institute of Public Administration and Research in Civil Protection
Vyshhorodska str., 21, Kyiv, Ukraine, 04074

An issue related to using cable products for building structures is to ensure their stability and durability when operating within wide limits. Therefore, the object of research was a change in the properties of the polymer sheath of the cable during the formation of a swollen coating layer under the influence of high temperature. It is proved that in the process of thermal action on the flame retardant coating, the process of thermal insulation of the cable involves the formation of particulate products on the surface of the sample. Under the action of the burner flame, a temperature was reached on the surface of the sample, which led to a swelling of the coating of more than 16 mm. The measured temperature on the inverse surface of the sample was no more than 160 °C, which indicates the formation of a barrier for temperature. In this regard, a calculation and experimental method for determining thermal conductivity when using a flame retardant as a coating has been developed, which makes it possible to estimate the coefficients of temperature conductivity and thermal conductivity under high-temperature action. According to the experimental data and established dependences, the coefficients of temperature conductivity and thermal conductivity of wood were calculated, which are $214.4\cdot10^{-6}$ m^2/s and 0.62 W/(m·K), respectively, due to the formation of a heat-insulating swollen layer. The maximum possible temperature penetration through the thickness of the coating was assessed. A temperature was created on the surface of the sample, which significantly exceeds the ignition temperature of the polymer sheath of the cable, and, on a non-heated surface, does not exceed 160 °C. Thus, there is reason to argue about the possibility of directed adjustment of the fire protection processes of an electrical cable by using coatings capable of forming a protective layer on the surface of the material, which inhibits the rate of heat transfer

***Keywords:** fire retardants for cable products, electrical cable, combustion of polymer cable sheath, cable surface treatment, coating*

Received date 04.01.2023
Accepted date 09.03.2023
Published date 30.04.2023

***How to Cite:** Tsapko, Y., Likhnyovskyi, R., Tsapko, A., Kovalenko, V., Slutska, O., Illiuchenko, P., Kravchenko, R., Sukhanevych, M. (2023). Determining the thermal-physical characteristics of a coke foam layer in the fire protection of cable articles with foaming coating. Eastern-European Journal of Enterprise Technologies, 2 (10 (122)), 22–30. doi: https://doi.org/10.15587/1729-4061.2023.275550*

1. Introduction

The existence of any settlement in today's conditions is difficult to imagine without the supply of electrical energy, both for the functioning of electrical equipment and for providing heat, water, and sewerage. Fire safety of electrical networks is determined by a number of factors, in particular, the compliance of the brand of conductor and the method of

Copyright © 2023, Authors. This is an open access article under the Creative Commons CC BY license

laying, the nature and properties of the environment. When assessing fire danger, internal shop electrical networks deserve the most attention since cables and wires in them are most often located openly in the form of harnesses. And the main reasons leading to the ignition of combustible material (insulation, protective cover of the shells) of cables and wires are emergency operating modes of electrical equipment. Therefore, cable and wire articles are an intermediate link between the source of energy and the place of its application that enables uninterrupted power supply and safe operation of any enterprise.

The sheath and insulation of cables mainly consists of combustible polymeric materials that, under the influence of an open flame, high conductor temperature, or due to a short circuit, can ignite and distribute the flame. Due to the passage of cable lines in transit through all premises, there is a risk of fire and fire spreading to other electrical networks. An example would be a fire at the Chernobyl nuclear power plant when overloading electrical cables led to their ignition. In turn, fireproof treatment of cable and wire articles with a special coating makes it impossible to spread the flame on the surface, reduces the burning rate, reduces the smoke formation of volatile articles and their toxicity and could cause self-attenuation.

The application of special flame-retardant coatings on an inorganic base is characterized by a rigid structure and, over time, low adhesion, which causes shedding and, when exposed to high temperature, leads to fire. In addition, the mechanism for protecting cable lines with coatings against the effects of fire temperature has not been sufficiently studied, which makes it impossible to obtain objective information about the nature of the processes that occur during operation. And the lack of theoretical ideas about the impact on their stability of flame retardants, which are swelling coatings, significantly limits the scale and prospects for the use of these materials.

Therefore, studies aimed at determining the patterns of inhibition of the combustion process of cable lines when treated with a swelling coating are relevant.

2. Literature review and problem statement

The purpose of article [1] was to obtain data using generally accepted standard tests that would make aallow for an unbiased analysis of the relative advantages of materials for fire hazard. The results indicate the following: materials may be suitable for use in wires and cables, regardless of their chemical composition. Halogen-containing materials, as a group, as a rule, are superior to non-halogen materials in terms of the basic properties of fire: heat dissipation, flammability, flame propagation. Most commercial materials tend to have appropriate mechanical and physical properties, but halogen-containing materials tend to be slightly more satisfactory. Compared to fire-resistant non-halogenated materials, halogen-containing materials tend to have better performance in terms of some of the more important electrical properties, in particular the dielectric breakdown voltage. The aging resistance of non-halogenated materials is somewhat suspicious, especially with regard to the effects of oils. Smoke absorption per unit mass of non-halogenated (polyolefin-based) materials is preferable than that of vinyl-based materials. But the differences are greatly reduced when we consider the expected eclipse of smoke during actual full-scale fires because of the tendency of halogen-containing materials to burn; the eclipse of smoke from fluorine-containing materials is also low. However, smoke corrosion is the only property where non-halogenated materials are clearly superior to halogenated materials.

In [2], compositions of ethylene-propylene-diene rubber containing mixtures of aluminum hydroxide (ATH) and soot (HAF) as insulation fillers in electrical wires and cables for fire resistance storage are given. After determining the flammability, the developed compositions were analyzed for the dielectric constant, dissipation coefficient, dielectric strength, volumetric and surface resistivity. It was found that for fire resistance the minimum amount of ATH should be 160 units. However, this composition contains 15 HAF units, which is harmful to electrical properties. Only a composition of 170/7.5 (ATH/HAF) showed the desired performance.

Paper [3] noted that damage and overheating of the insulation of wires is the main source of ignition in the case of fire. Since, for fire safety on manned spacecraft, it is very important to study the occurrence of a fire insulation of wires under microgravity conditions. Therefore, the influence of ambient pressure, wire diameter, number of wire harnesses and overload currents was studied with an emphasis on constant equilibrium temperature and the rate of increase in wire insulation temperature using the functional modeling method. The results are important for studying the harbinger of fire under microgravity conditions and have been used to determine experimental parameters, but it is not specified what measures need to be taken to increase the fire resistance of the cable.

The propagation of the flame through the wire with polymer insulation at a reduced (below atmospheric) pressure was investigated experimentally in [4] in order to assess the fire safety of the electrical circuit in the aircraft, as well as space environments. As a combustion sample, NiCr wire with polyethylene (PE) insulation is used. Experimental results show that the shape of the flame varies from typical “teardrop-shaped” to “round” (and even oval) with a decrease in total pressure. The rate of flame propagation increases at reduced pressure, although the partial pressure of oxygen “decreases” along with the total pressure. This “pronounced” distribution behavior is observed continuously to a state immediately before extinction (approximately 25 kPa in this study). Changing the shape of the flame can increase the flow of heat to unburned polyethylene due to the conductivity in the gas phase, as well as conductivity along the wire, and they must be responsible for the faster propagation of the flame at pressures below atmospheric. The heat balance is approximately estimated by the measured temperature, and the relative contribution of the above two heat input paths is considered almost comparable. But issues related to the presence of metal wire remain unresolved.

Polyamide structural plastics, as stated in [5], demonstrate excellent mechanical properties (for example, high strength at high temperatures, viscosity at low temperatures, and good resistance to wear and abrasion) and chemical resistance. They are used in automotive parts, electrical/electronic devices, and industrial applications (PA). In most of these applications, PA must meet some critical fire standards, such as UL 94, comparative tracking index (CTI), and glow wire testing (GWFI/GWIT). This document will examine modern halogen-containing PA technology and problems in commercial applications. More importantly, the latest advances in halogen-free PA will be presented. The mode of action of these flame retardants in PA will also be considered. However, issues related to the ability to maintain color and resistance to destruction remained unresolved.

In [6], the standard IEC 60335-1 was investigated that establishes new limits on the ignition temperature of the hot wire (GWIT) for materials used for electrical connectors. GWIT and CTI properties for three technical thermoplastic polymers (PBT, PET, and PC) have also been reported. They also investigated the phenomena associated with this test, considering phenomena using a parameterization approach that has already been used in studies of the behavior of polymers in fire. PC, PBT, and PET, filled with 30 wt % fiberglass have been tested, and material properties that may be related to GWIT and CTI characteristics have been measured by TGA, Laser Flash Thermal Diffusivity (LFTD), Pyrolysis-GC/MS. CTI correlates with the tendency to form charring materials, so PBT shows higher tracking resistance than PET and PC. Polycarbonate was the only material to be tested on hot wire (GWIT above 775 °C). In general, GWIT performance is not directly related to the degradation temperature as PET is thermally more stable compared to PBT but less stable in hot wire testing. The ignition process, as well as the non-stationary heat and mass transfer process characteristic of testing hot wire, is affected by many parameters simultaneously. But the results of TGA, laser flash, pyrolysis-GC/MS remain unrelated to the ignition temperature of the hot wire of the materials under study.

In [7], a life cycle assessment (LCA) is given to compare polymer coatings hardened with nanoclay with conventional ones. The main purpose of that study was to compare the environmental impact of wire coating (mineral flame retardants such as ATH or MDH in a polymer matrix) with a wire coating hardened with a low amount of nanoclay. The system limits of the study include the following single processes: the production of nanoclay, the production of thermoplastic materials and mineral flame retardants, the production of cable coating by extrusion, and various end-of-life scenarios (processing, incineration, and disposal in landfills). While nano-reinforced composites have demonstrated increased fire resistance, the addition of nanomaterials is not essential for environmental evaluation. The absence of nanospecific factors for nanomaterials and emission levels is mainly in the extrusion and use phase where accidental combustion may occur. However, it is still a challenge to model the assessment of its life cycle.

Article [8] lists a high-temperature superconducting device (HTS) that demonstrates several advantages, including low volume, low weight, high efficiency, strong overload capacity, and no risk of fire. When HTS devices operate in a power supply system, superconducting tapes can go out due to a malfunction of the power supply system and withstand electromagnetism and mechanical stress caused by large or unbalanced current. This document first introduces a core cable that has a copper form, a conductor layer, and an insulation layer. Then a simulation experiment is proposed on the thermal stability of the superconducting winding using the cable core to analyze temperature and voltage curves under quenching conditions with various thermal perturbations. Using a combination of stability theory, we estimate the rate of spread of quenching and analyze the factors affecting the rate of propagation of quenching and the minimum extinguishing energy. When the main cable's quenching propagation speed is higher, it is efficient and convenient for monitoring the situation and diagnosing HTS device malfunctions.

Polymer insulation dripping, as indicated in [9], is a different type of dangerous behavior during a wire fire, which has a potential risk of ignition of adjacent combustible material. This is the reason for the sharp growth and spread of fire in buildings, airplanes, spacecraft, and nuclear power plants. To improve the fire safety strategy, bench tests are being carried out to study the phenomenon of dripping using a sample of thin wire under various atmospheric pressures and electric current. The results show that the change in the flame front has small vibrations during the dripping of the melt, while the size of the flame (especially the height of the flame) varies significantly. In addition, the dripping frequency (f) decreases with pressure (P) due to a sufficient combustion effect but increases with electric current (I) due to a stronger cumulative effect.

In [10] it is noted that the main condition for fire resistance is that wire breaks or short circuits cannot occur in the cable system. To do this, wires from various plastic shells were subjected to flame and heating, and also checked at what actual oxygen content they begin to burn and spread the flame. In addition, they investigated how fire-resistant cables react to possible overvoltage during spontaneous combustion. The results showed that factory certificates are not enough to ensure complete fire safety. For example, plastic PH 180, E90 received the lowest LOI value. PH 30 and PH 120 confirmed their flammability. Due to the complex layers that are being investigated, their testing is complex and requires a variety of tests to obtain complete combustion behavior. The most important exothermic peaks of the charts give the expected LOI values. The first and second decomposition indicate only damage and smoke, that is, only according to the results of overload tests.

Assessment of environmental conditions under which fire-fighting equipment is triggered is one of the main design tasks that must be taken into account when developing electrical systems that supply such devices [11]. All solutions are aimed, among other things, at preserving the environmental parameters in the building that burns for the estimated time and at a level that ensures safe evacuation. These parameters include temperature, thermal radiation, range of visibility, oxygen concentration, and environmental toxicity. A new mathematical model of heat transfer between the environment and an electrical cable under thermal conditions exceeding the permissible values for commonly used non-combustible mounting cables is presented. To simulate the heat flux, the method of analogy between thermal and electrical systems was used. The definition of how the thermal conductivity of the cable and the heat capacity of the conductor-insulation system can be applied to calculate the temperature of the wire depending on the heating time t and the distance x from the heat source is discussed. Thermal conductivity and capacitance were determined on the basis of experimental tests of halogen-free flame retardant (HFFR) cables with a wire cross-section of 2.5, 4.0, and 6.0 mm^2. However, the experimental tests carried out make it possible to check the results calculated according to the mathematical model.

To calculate the temperature of the insulating layer, paper [12] built a mathematical model of an electrified insulated cable. The temperature of the insulating layer is defined as a function of current strength, time, thickness of the insulating layer, etc. As an example, a widespread polyvinyl chloride (PVC) cable with a cross-sectional area of 4 mm^2 was selected and the temperature of its insulation layer was modeled using ANSYS. The simulation revealed a change in the temperature of the insulation layer over time, as well as along the radius after a certain time, when the cable was superimposed with a direct current of 40 A and 60 A, respectively. The analysis method is of practical importance to prevent an electric fire and can be used to analyze a spontaneous combustion accident involving an insulated cable.

To determine the fire resistance of cables, two popular methods of fire protection were used in [13], one of which is to apply a fire retardant coating directly to the cable surface. And the other is in placing the cable in a metal pipe coated with a fire-retardant coating based on structured steel. The results showed that for both methods of protection, the cable failure time increased with the thickness of the coating. However, if the applied flame-retardant coating of the cable has a thickness of more than 1.5 mm, then it is destroyed when the cable is moved. When the coating based on structured steel was thinner than 1 mm or thicker than 3 mm, the protective effect was not noticeable due to the relatively small multiple expansion. However, neither of the two methods has been effective in protecting electrical cables that supply power to the equipment needed to operate in a fire for a long time.

Thus, from literary sources it has been established that during the operation of cable lines their ignition is possible, which requires effective protection with environmentally friendly substances. In addition, the parameters that provide resistance to thermal effects of coatings are not defined. The lack of mathematical models to explain and describe the process of fire protection of cables, neglect of the use of organic substances for the formation of elastic coatings leads to inefficient use of protective equipment. Therefore, the establishment of the parameters of the stability of the polymer shells of the cable to thermal destruction and the effect of coatings on this process necessitated research into this area.

3. The aim and objectives of the study

The aim of this work is to establish the patterns of formation of fire-retardant coating on the surface of the sheath of the electrical cable. This makes it possible to justify the directions of expanding the scope of application of articles made of electrical cables.

To accomplish the aim, the following tasks have been set:

– to simulate the process of thermal conductivity in the formation of a swollen coating layer under the influence of high temperature;

– to establish the features of temperature inhibition through the swollen layer of coke to the cable during thermal effects on the flame-retardant coating.

4. The study materials and methods

4. 1. Research hypothesis

The object of our study is a change in the thermophysical properties of the polymer sheath of the cable during the thermal decomposition of the coating. The sscientific hypothesis assumes the use of a swelling coating for fire protection of a cable that can, under the influence of high temperature, create a heat insulating swollen coating layer on the surface of the polymer shell.

4. 2. The studied materials used in the experiment

For the research, a control copper cable KVVG 4×1.5 was used (cross-section of the core, 1.5 mm^2; number of cores, 4, insulation of cores/cable sheath – PVC compound/PVC compound), Fig. 1.

Fig. 1. Cable sample for research

To study the effectiveness of cable fire protection, a coating "FireWallWood" (manufactured in Ukraine) was applied to the surface, capable of swelling under the influence of high-temperature exposure [14]. The coating consumption was 147.0–150.0 g/m^2.

After drying to a constant mass of the coating, the processed cable samples were tested for protection efficiency.

4. 3. Procedure for determining the indicators of fire protection of fabrics with an intumescence coating

To conduct research on the fire protection of the cable, special equipment with a gas burner modeling the source of ignition was used (Fig. 2).

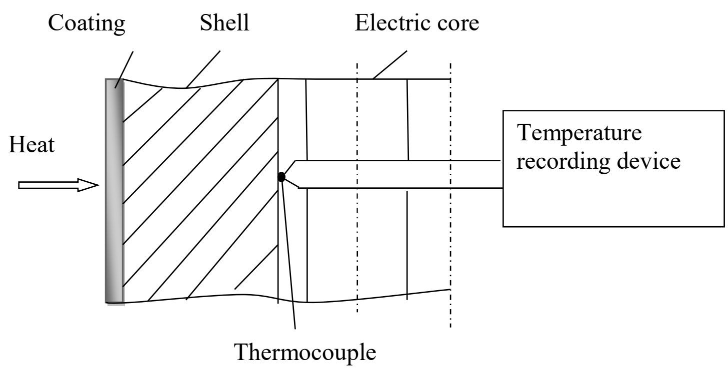


Fig. 2. Device to study thermal conductivity of a fireproof cable

Determination of the flame-retardant properties of the coated cable was carried out by assessing the combustion characteristics of the cable under the action of a flame in the controlled laboratory setting [15]. Inside a sample of the electric cable with the applied coating, the thermocouple was placed and fixed in the sample holder. For research, a test unit is used in which a sample of a cable with a length of 200 mm is fixed. Surface tests are carried out under the action of a burner for 300 s, for the burner was installed in an upright position with a flame height of 40 mm. To do this, the burner was brought to the sample cable to set it on fire and measure the temperature on the rear surface.

The criterion for determining the thermal conductivity of the flame-retardant coating under thermal action is the formation of a temperature on the inner surface of the cable sheath, which does not exceed the ignition temperature. At the same time, the swelling of the coating is fixed in the form of a layer that is located between the heating medium and the starting material. Using the measured temperature values, the thermal insulation properties of the swollen layer were calculated.

To simulate the process of thermal conductivity of the swollen coating layer during thermal action on a cable, the main provisions of mathematical physics were applied [16].

5. Results of determining the thermophysical characteristics of the swelling layer of cable coating under thermal exposure

5. 1. Modeling of thermophysical characteristics for a layer of swollen coating on the surface of cable articles under thermal action

Under the action of heat flow on samples of fireproof cable, the process of formation of non-combustible gases and a highly flammable coke oven layer takes place, which absorbs heat and reduces heat transfer to the material.

Taking into account that the determination of the thermophysical characteristics of the swollen coating layer is associated with measuring the temperature within a thickness of 0.5÷1 mm. Therefore, to establish the thermophysical characteristics of the heat-insulating swollen coating layer formed on the cable sheath, a method for solving the problem of thermal conductivity for a two-part rod with different thermophysical properties is proposed [17]. At the initial point in time, the outer surface of the rod is heated to the insulation decomposition temperature constant throughout the time and the temperature distribution passes through the swollen layer until the critical temperature of the cable sheath is reached.

To this end, two areas are considered (Fig. 3):

1 – zone of the swollen coating layer, $0<x\leq R$ (R – coordinate of formation of the swollen coating layer, m);

2 – cable sheath $R\leq x\leq\infty$.

Differential equations for heat transfer on the surface of a flame-retardant cable, representing two cylinders, take the form [18]:

– for a coating:

$$a_1\frac{\partial^2 T_1(x,\tau)}{\partial x^2}-\frac{\partial T_1(x,\tau)}{\partial \tau}=0,\ (\tau>0;\ 0<x<R);\qquad(1)$$

– for cable sheath:

$$a_2\frac{\partial^2 T_2(x,\tau)}{\partial x^2}-\frac{\partial T_2(x,\tau)}{\partial \tau}=0,\ (\tau>0;\ R<x<\infty),\qquad(2)$$

with initial and boundary conditions:

$$T_1(x,0)=T_2(x,0)=0,\qquad(3)$$

$$T_1(R,\tau)=T_2(R,\tau)=0,\qquad(4)$$

$$\lambda_1\frac{\partial T_1(x,\tau)}{\partial x}=\lambda_2\frac{\partial T_2(x,\tau)}{\partial x},\qquad(5)$$

$$T_1(x,\tau)=T_c=\text{const},\qquad(6)$$

$$T_2(\infty,\tau)=0,\qquad(7)$$

where a_1, a_2 – coefficients of temperature conductivity of the coating and cable;

λ_1, λ_2 – coefficients of thermal conductivity of the coating and cable;

R – coating thickness.

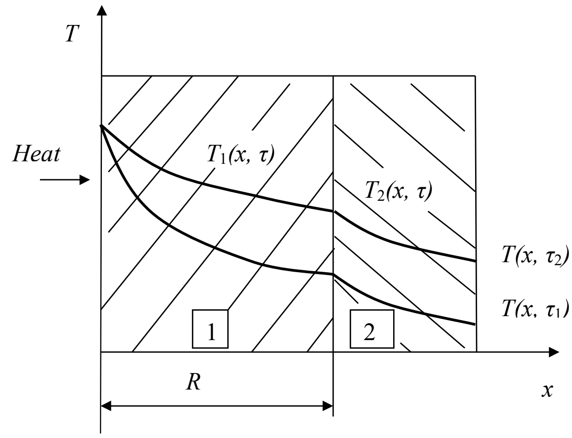


Fig. 3. Scheme of the process of fire protection of the cable sheath: 1 – swollen coating layer; 2 – cable sheath

The solution to equations (1) and (2) with initial and boundary conditions (3) to (7) is considered in article [19] as dependences:

$$\theta_1=\frac{T_1(x,\tau)}{T_c}=erfc\frac{x}{2\sqrt{a_1\cdot\tau}}-$$
$$-h\sum_{n=1}^{\infty}h^{n-1}\left[erfc\frac{2n\cdot R-x}{2\sqrt{a_1\cdot\tau}}-erfc\frac{2n\cdot R+x}{2\sqrt{a_1\cdot\tau}}\right];\qquad(8)$$

$$\theta_2=\frac{T_2(x,\tau)}{T_c}=$$
$$=\frac{2K_\varepsilon}{1+K_\varepsilon}\sum_{n=1}^{\infty}l^{n-1}\cdot erfc\left[\frac{x-R+(2n-1)\cdot K_a^{-1/2}\cdot R}{2\sqrt{a_2\cdot\tau}}\right],\qquad(9)$$

where $K_\varepsilon=\frac{\lambda_1}{\sqrt{a_1}}\cdot\frac{\sqrt{a_2}}{\lambda_2}$; $h=\frac{1-K_\varepsilon}{1+K_\varepsilon}$; $K_a^{-1/2}=\sqrt{\frac{a_2}{a_1}}$.

So, in particular, equation (8) shows the temperature distribution in the swollen coating layer; thickness measurement is a difficult task. Therefore, it is proposed to analyze equation (9), which depicts the distribution of temperature in cable insulation. At low values of the cable sheath (0.5÷1.0 mm), the convergence of the series (9) increases, and the temperature value is quite accurately described by the first term [19]:

$$\theta_2=\frac{2K_\varepsilon}{1+K_\varepsilon}\ erfc\left[\frac{x-R\cdot K_a^{-1/2}\cdot R}{2\sqrt{a_2\cdot\tau}}\right].\qquad(10)$$

Given the above, the determination of the thermophysical characteristics of the swollen coating layer can be carried out according to the following scheme.

Suppose that at the point $x=R$ at time τ_1 the temperature will be:

$$\theta_{x=R}=\frac{2K_\varepsilon}{1+K_\varepsilon}\ erfc\frac{R}{2\sqrt{a_1\cdot\tau_1}},\qquad(11)$$

and at the point $x>R$ the temperature is reached in time τ_2 and will be:

$$\theta_{x>R}=\frac{2K_\varepsilon}{1+K_\varepsilon}\,erfc\left(\frac{x-R+K_a^{-1/2}\cdot R}{2\sqrt{a_2\cdot\tau_2}}\right). \quad (12)$$

Thus, at time τ_1, the relative temperature at point $x=R$ is θ_1, and at time is τ_2–θ_2, respectively.

Given that the function *erfc X* is unambiguous [18] we equate equations (11) and (12) to derive the dependence:

$$\frac{R}{2\sqrt{a_1\cdot\tau_1}}=\left(\frac{x-R+K_a^{-1/2}\cdot R}{2\sqrt{a_2\cdot\tau_2}}\right). \quad (13)$$

Under condition:

$$K_a^{-1/2}=\sqrt{\frac{a_2}{a_1}}, \quad (14)$$

we solve equation (13) and obtain an expression to determine the temperature conductivity coefficient of the swollen coating layer:

$$a_1=\frac{a_2\cdot R^2}{\tau_1\cdot(x-R)^2}\left(\sqrt{\tau_2}-\sqrt{\tau_1}\right)^2. \quad (15)$$

We substitute (15) in (10) and get an expression to determine the thermal conductivity coefficient of the swollen coating layer:

$$\lambda_1=\frac{\lambda_2\cdot R\cdot\left(\sqrt{\tau_2}-\sqrt{\tau_1}\right)}{(x-R)\cdot\sqrt{\tau_1}\cdot\left(\frac{2}{\theta_2}\cdot erfc\frac{x-R}{2\sqrt{a_2}\cdot\left(\sqrt{\tau_2}-\sqrt{\tau_1}\right)}-1\right)}. \quad (16)$$

Thus, we have established the estimation dependences (16) and (15) that allow us to obtain thermophysical characteristics for the layer of a swollen coating according to experimental values of temperature difference and known values of thermal conductivity and temperature conductivity of the shell material.

5. 2. Results of temperature determination through a swollen coating layer to the cable under thermal exposure

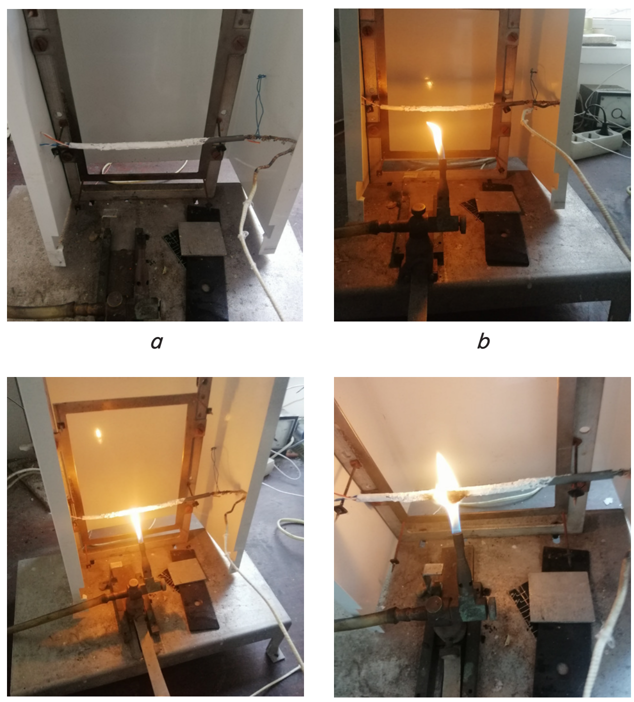
To obtain the flame-retardant efficiency of the coating for a sample of an electrical cable, studies were conducted on its ignition under the action of a burner that simulates a source of ignition. The results of studies on determining the flammability of a fireproof cable sample are shown in Fig. 4, 5.

During the thermal effect of the burner on the samples of the fireproof cable, the coating began to swell and a slight increase in temperature on the inner surface of the cable occurred. As a result of the tests, it was found that under the influence of a flame for 300 s, the swelling for a model sample of fabric treated with a flame-retardant composition was more than 20 mm.

The results of research on the experimental determination of temperature on the inner surface of the cable shell in the form of an experimental curve are shown in Fig. 6.

Studies have shown that under the action of a burner flame, a sample of a fireproof cable withstood thermal effects. Under the action of high temperature, the coating was swelled for 280 s; the temperature on the inverse surface of the cable sheath did not exceed 160 °C.

The thermophysical characteristics of the polymer shell are determined in [20], the results are given in Table 1. Given that the heat flux of the flame of the gas burner is about 10100 kW/m^2 [21], and the flame temperature of the gas burner is about 1000 °C [22], a temperature was created on the surface of the polymer sheath of the cable that exceeds the decomposition temperature of the material by several times. Taking into account the results of temperature measurements (Fig. 6) and using the obtained dependences (16) and (15), the thermophysical properties of the swollen coating layer are determined. To do this, we selected the period of time when the swollen coating layer was formed under the action of a gas burner; Fig. 6. Thus, the coefficient of temperature conductivity of the swollen coating layer is 214.4·10^{-6} m^2/s, and the thermal conductivity coefficient was 0.62 W/(m·K), respectively.



a *b* *c* *d*

Fig. 4. Determination of flammability of a fireproof cable sample under the action of a burner: *a* — fastening of the cable sample; *b* — setting the height of the flame; *c* — ignition of the cable sample; *d* — combustion of cable sample

Fig. 5. Cable sample swelling

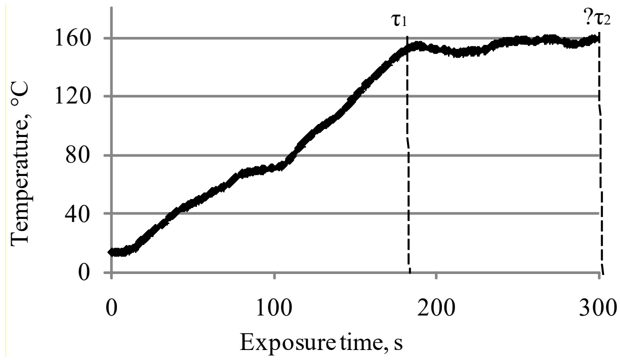


Fig. 6. Temperature on the inverse surface of the cable sheath when exposed to a burner flame

Table 1

Thermophysical characteristics of cable sheath (polyvinyl chloride) [20] and swollen coating layer

Material name	Thick-ness, mm	Thermophysical insulation characteristics			
		Density ρ, g/m^3	Conductivity temperature, m^2/s	Thermal conductivity λ, W/(m·K)	Nominal heat capacity, kJ/(kg·K)
Polyvinyl chloride	1.1	1.2	$12\cdot10^{-6}$	0.15	1.2
Swollen coat-ing layer	16	0.82	$214.4\cdot10^{-6}$	0.62	3.53

The results of studies on the determination of the thermophysical characteristics of the swollen coating layer of the fireproof cable sample correspond to the properties of the heat-resistant layer of foam coke [23]. The absence of cable combustion shows the resistance of the flame-retardant coating to the effects of high flame temperature and justifies the effectiveness of protection [24].

6. Discussion of results of studying the process of formation of a layer of foam coke in the fire protection of fabric

In the study of the process of fire protection of the cable with a swelling coating, as it follows from our results (Table 1, Fig. 6), it is natural to extend the time of temperature transfer through a fire-unprotected cable. This is due to the formation of a layer of swollen coke layer on the surface of a fireproof cable during the decomposition of flame retardants, which slows down the processes of heat transfer to the polymer shell and its combustion.

It should be noted that the presence of a modified swelling coating leads to the formation of an elastic film on the surface of the polymer shell resistant to mechanical vibrations [25]. Obviously, such a mechanism of influence of an elastic film is the factor in regulating the process by which the fire resistance of the cable is maintained. This is the sense of the interpretation of the results of determining the swelling layer of the coating after exposure to the flame, namely the magnitude of the swelling of samples under thermal exposure. Since the layer the coating reached a value of more than 16 mm, and the temperature on the inverse surface of the sample was no more than 160 °C. This indicates the formation of a barrier for temperature, which can be identified by the method of thermal exposure of the investigated samples.

This means that taking into account this fact opens up the possibility for effective adjustment of the properties of the fireproof cable directly under the conditions of serial industrial production.

Comparison of experimental studies on the determination of heat insulation of the coke layer during cable fire protection and theoretical studies of thermal insulation of the polymer shell indicates the inhibition of heat transfer processes. Since the temperature on the inverse surface under the action of the burner did not exceed 160 °C, and the coating layer reached a value of more than 16 mm (Fig. 5).

This does coincide with the practical data known from [3, 5], the authors of which, by the way, also associate the effectiveness of fire protection with the formation of a layer of coke foam under the influence of a burner flame. But, unlike the results of studies published in [26, 27], the data obtained on the effect of a swelling coating on the process of inhibiting temperature transmission suggest the following:

– the main regulator of the process is not so much isolation from the effects of air but also the formation of a significant amount of gases that inhibit the flame since individual flame retardant coatings are destroyed under the influence of high temperature;

– a significant impact on the cable protection process when using a flame-retardant coating is exerted in the direction of formation of a layer of coke from an elastic film on the surface of the polymer shell resistant to destruction under the influence of vibrations of the product.

Such conclusions may be considered appropriate from a practical point of view since they allow for a reasonable approach to determining the required amount of fire retardant. From a theoretical point of view, this suggests the definition of the mechanism of temperature inhibition processes, which are certain advantages of this study.

However, it is impossible not to note that the results of the determination (Fig. 5) indicate the ambiguous effect of the foam layer on the change in fire retardant efficiency. This is manifested primarily in the temperature on the inverse surface of the sample during tests of a fireproof cable. Such uncertainty imposes certain restrictions on the use of the results obtained, which can be interpreted as the shortcomings of this study. The disadvantage for the formed swollen coating layer for a fireproof cable is the high temperature, which must be reduced much lower than the decomposition temperature of the polymer cable sheath. The inability to remove these restrictions in the framework of this study gives rise to a potentially interesting direction for further research. In particular, it can be focused on identifying the moment in time from which the fall in flame retardant properties begins and the cable ignites under the influence of high temperature. Such detection will allow us to investigate the structural transformations of the elastic film of the coating, which begin to occur at this time, and to determine the input variables of the process that significantly affect the beginning of such a transformation.

7. Conclusions

1. We have simulated the process of heat transfer through the swollen layer during its protection by a swelling coating

and obtained dependences that allow us to obtain a change in the dynamics of heat transfer and determine the thermophysical properties of the swelling layer of the coating. According to experimental data and the derived dependences, the coefficients of temperature conductivity and thermal conductivity of wood were calculated, which are $214.4 \cdot 10^{-6}$ m^2/s and 0.62 W/(m·K), respectively, due to the formation of a heat-insulating swollen layer.

2. Features of braking the process of heat transfer to the material treated with a flame retardant coating are the formation of a heat-shielding swollen coating layer on the cable surface. Thus, a temperature was created on the surface of the sample, which significantly exceeded the ignition temperature of the polymer sheath of the cable, and, on a non-heated surface, did not exceed 160 °C.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

Acknowledgments

The authors express their gratitude for the development of scientific topics in the program of scientific cooperation COST Action CA18223 "Future communications with higher-symmetric engineered artificial materials" within the framework of the European Union's HORIZON2020 program.

References

1. Barnes, M. A., Briggs, P. J., Hirschler, M. M., Matheson, A. F., O'Neill, T. J. (1996). A Comparative Study of the Fire Performance of Halogenated and Non-Halogenated Materials for Cable Applications. Part I Tests on Materials and Insulated Wires. Fire and Materials, 20 (1), 1–16. doi: https://doi.org/10.1002/(sici)1099-1018(199601)20:1<1::aid-fam553>3.0.co;2-w
2. Canaud, C., Visconte, L. L. Y., Sens, M. A., Nunes, R. C. R. (2000). Dielectric properties of flame resistant EPDM composites. Polymer Degradation and Stability, 70 (2), 259–262. doi: https://doi.org/10.1016/s0141-3910(00)00124-5
3. Kong, W.-J., Wang, B.-R., Lao, S.-Q. (2007). Study on fire precursor of wire insulation in low-pressure environments. Journal of Engineering Thermophysics, 28 (6), 1047–1049.
4. Nakamura, Y., Yoshimura, N., Matsumura, T., Ito, H., Fujita, O. (2007). Flame Spread Along PE-Insulated Wire in Sub-Atmospheric Pressure Enclosure. ASME/JSME 2007 Thermal Engineering Heat Transfer Summer Conference, Volume 1. doi: https://doi.org/10.1115/ht2007-32657
5. Shen, K. K., Kochesfahani, S., Jouffret, F. (2010). Fire retardant polyamides-present technology and challenges. 21st Annual Conference on Recent Advances in Flame Retardancy of Polymeric Materials. Available at: https://www.researchgate.net/publication/286798401_Fire_retardant_polyamides-present_technology_and_challenges
6. Acquasanta, F., Berti, C., Colonna, M., Fiorini, M., Karanam, S. (2011). Study of Glow Wire Ignition Temperature (GWIT) and Comparative Tracking Index (CTI) performances of engineering thermoplastics and correlation with material properties. Polymer Degradation and Stability, 96 (4), 566–573. doi: https://doi.org/10.1016/j.polymdegradstab.2010.12.024
7. Tellaetxe, A., Blázquez, M., Arteche, A., Egizabal, A., Ermini, V., Rose, J. et al. (2012). Life cycle assessment of the application of nanoclays in wire coating. IOP Conference Series: Materials Science and Engineering, 40, 012014. doi: https://doi.org/10.1088/1757-899x/40/1/012014
8. Fu, S., Qiu, M., Zhang, H., Zhu, J., Liu, H. (2016). Analysis of Thermal Stability of Superconducting Windings Using Core Cable With YBCO Coated Conductors. IEEE Transactions on Applied Superconductivity. doi: https://doi.org/10.1109/tasc.2016.2535976
9. Wang, Z., Li, H. H., Wang, J. (2018). Dripping Behavior of Wire Fire under Varying Pressure and Electric Current. Key Engineering Materials, 775, 7–12. doi: https://doi.org/10.4028/www.scientific.net/kem.775.7
10. Kerekes, Z., Restás, Á., Lublóy, É. (2019). The effects causing the burning of plastic coatings of fire-resistant cables and its consequences. Journal of Thermal Analysis and Calorimetry, 139 (2), 775–787. doi: https://doi.org/10.1007/s10973-019-08526-9
11. Perka, B., Piwowarski, K. (2021). A Method for Determining the Impact of Ambient Temperature on an Electrical Cable during a Fire. Energies, 14 (21), 7260. doi: https://doi.org/10.3390/en14217260
12. Li, X., Yang, J., Yan, B., Zheng, X. (2018). Insulated Cable Temperature Calculation and Numerical Simulation. MATEC Web of Conferences, 175, 03014. doi: https://doi.org/10.1051/matecconf/201817503014
13. Wang, J., Shu, Z.-J., Chen, Z. (2013). The protective effect of a fire-retardant coating on the insulation failure of PVC cable. Engineering Failure Analysis, 34, 1–9. doi: https://doi.org/10.1016/j.engfailanal.2013.07.010
14. Tsapko, Y., Bondarenko, O., Tsapko, A., Sarapin, Y. (2022). Application of Coating for Fire Protection of Textile Structures. Key Engineering Materials, 927, 115–121. doi: https://doi.org/10.4028/p-vd6w4b

15. Likhnyovskyi, R., Tsapko, A., Kovalenko, V., Onyshchuk, A. (2022). Application of Intumescent Coating for Increasing Fire-Resistance Values of Cable Products. Key Engineering Materials, 927, 105–114. doi: https://doi.org/10.4028/p-2c1e3p
16. Tsapko, Y., Tsapko, A., Bondarenko, O., Chudovska, V. (2021). Thermophysical characteristics of the formed layer of foam coke when protecting fabric from fire by a formulation based on modified phosphorus-ammonium compounds. Eastern-European Journal of Enterprise Technologies, 3 (10 (111)), 34–41. doi: https://doi.org/10.15587/1729-4061.2021.233479
17. Janna, W. S. (2009). Engineering Heat Transfer. CRC Press, 692. Available at: https://www.routledge.com/Engineering-Heat-Transfer/Janna/p/book/9781420072020
18. Potter, M. C. (2019). Engineering analysis. Springer, 434. doi: https://doi.org/10.1007/978-3-319-91683-5
19. Lykov, A. V. (1967). Teoriya teploprovodnosti. Moscow: «Vysshaya shkola», 600. Available at: https://www.twirpx.com/file/2286982/
20. Uwa, C. A., Abe, B., Nnachi, A. F., Sadiku, E. R., Jamiru, T. (2021). Experimental investigation of thermal and physical properties of nanocomposites for power cable insulations. Materials Today: Proceedings, 38, 823–829. doi: https://doi.org/10.1016/j.matpr.2020.04.670
21. Bronin, F. A. (2008). Gorelki laboratornye. Ustroystvo i kharakteristiki. Available at: http://www.bststgr.narod.ru
22. Kryzhanovskiy, V. N., Kryzhanovskiy, Yu. V. (2012). Struktura i raschet gazovogo fakela. Kyiv: «Osvita Ukrainy», 96. Available at: https://ela.kpi.ua/handle/123456789/2264
23. Tsapko, Y., Horbachova, O., Mazurchuk, S., Tsapko, A., Sokolenko, K., Matviichuk, A. (2022). Establishing regularities of wood protection against water absorption using a polymer shell. Eastern-European Journal of Enterprise Technologies, 1 (10 (115)), 48–54. doi: https://doi.org/10.15587/1729-4061.2022.252176
24. Tsapko, Y., Lomaha, V., Vasylyshyn, R., Melnyk, O., Balanyuk, V., Tsapko, A. et al. (2022). Establishing regularities in the reduction of flammable properties of wood protected with two-component intumescent varnish. Eastern-European Journal of Enterprise Technologies, 3 (10 (117)), 63–71. doi: https://doi.org/10.15587/1729-4061.2022.259582
25. Tsapko, Y., Tsapko, A., Bondarenko, O. (2021). Defining patterns of heat transfer through the fire-protected fabric to wood. Eastern-European Journal of Enterprise Technologies, 6 (10 (114)), 49–56. doi: https://doi.org/10.15587/1729-4061.2021.245713
26. Tsapko, Y., Rogovskii, I., Titova, L., Bilko, T., Tsapko, A., Bondarenko, O., Mazurchuk, S. (2020). Establishing regularities in the insulating capacity of a foaming agent for localizing flammable liquids. Eastern-European Journal of Enterprise Technologies, 5 (10 (107)), 51–57. doi: https://doi.org/10.15587/1729-4061.2020.215130
27. Tsapko, Y., Rogovskii, I., Titova, L., Shatrov, R., Tsapko, A., Bondarenko, O., Mazurchuk, S. (2020). Establishing patterns of heat transfer to timber through a protective structure. Eastern-European Journal of Enterprise Technologies, 6 (10 (108)), 65–71. doi: https://doi.org/10.15587/1729-4061.2020.217970