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Requirements for cables as categories of construction products and thermal resistance of power cables

Introduction*. One of the main driving factors of the demand for cable and conductor products is the modern trend of urbanization, which leads to an increase in cities with significantly increased requirements for electrical networks of transportation and distribution of electrical energy. This requires the development of appropriate infrastructure with significant demand for electricity in the commercial, industrial and residential sectors. The construction industry uses a wide range of cables with an appropriate set of electrical and mechanical properties, resistance to the influence of external climatic factors, and, first of all, must meet fire safety requirements. Increasing construction activity is stimulating the market for fire-resistant cables in the construction industry. According to the Construction Products Regulation, power, telecommunication cables, data cables, control and management, fiber optic refer to construction products in the EU member states. These cables are intended for the supply of electrical energy and communication, which are permanently installed in buildings and other engineering structures. Power, telecommunications, data and control cables are considered construction products, and are the only electrical products classified as construction. Over the next 15 years, Eastern Europe is expected to see increased growth in the construction industry, as the end of the war in Ukraine requires nearly $1 trillion in reconstruction. A strategic task in the reconstruction of the country is the use of cable and conductor products with increased operational properties, including in the construction industry. Significant efforts and investments in innovation and certification of cable and conductor products require manufacturers to create construction products of the «Power, control and communication cables» category with a high level of fire safety in accordance with the Euroclassification of cables in terms of reaction to fire depending on the level of safety.* ***Purpose.*** *Analysis of fire safety requirements for cables as a category of construction products and determination of thermal resistance of power cables based on experimental thermal studies of modern electrical insulating compositions.* ***Methodology.*** *The thermal stability of power cables with a voltage of 0,66/1 kV was determined, depending on the design, based on the conducted experimental studies of the thermal stability of electrical insulation materials, between the core filling and the polymer sheath, removed from the cable samples. On the basis of the conducted correlation analysis between thermal resistance and fire load, which are important parameters for confirming the quality and safety of the entire cable, it has been proven that the efficiency of halogen-free compositions to meet fire safety requirements increases with the increase in the cross-section and number of cores in the cable.* ***Practical value****. Determining the heat load and fire resistance of cables of various designs and areas of application based on the obtained experimental data on the heat of combustion of polymer cable materials is necessary and justified at the stage of mastering and determining the prospects for the production of cables with modern halogen-free electrical insulation compositions in accordance with fire safety requirements.* References 40, figures 6.
Key words: **urbanization, construction industry, cable infrastructure, fire safety, cable classification criteria, halogen-free compositions, power cables, thermal resistance, fire load, certified test base.**

Проаналізовано світові тенденції урбанізації та їх вплив на розвиток кабельної індустрії. Представлено основні тренди розвитку будівельної галузі як рушійної сили сегменту вогнестійких та пожежобезпечних кабелів для забезпечення сучасної силової та інформаційної інфраструктури. Акцентовано на темпах застосування пожежобезпечних кабелів з низьким вмістом диму та безгалогенними композиціями у Європі. Зазначено, що для забезпечення жорстких вимог щодо пожежної безпеки кабельної інфраструктури у будівельному секторі введено узагальнену категорію «Силові, контрольні кабелі та кабелі зв'язку». Представлено класифікацію кабелів за пожежною ознакою відповідно до Регламенту будівельної продукції Європейського Союзу. Наведено критерії класифікації та методи випробувань для визначення вогнестійких характеристик кабелів відповідно до кількості випромінюваного тепла. Визначено теплову стійкість та пожежне навантаження в залежності від застосованих композитних полімерних галогеновмісткіх та безгалогенних композицій і конструктивного виконання силових кабелів низької напруги. Підтверджено ефективність безгалогенних композицій для забезпечення вимог щодо пожежобезпеки для кабелів з більшим діаметром струмопровідної жили та кількістю жил. Наголошено на необхідності створення відповідної сучасної сертифікованої випробувальної бази для визначення пожежної стійкості будівельної продукції категорії «Силові, контрольні кабелі та кабелі зв'язку». Бібл. 40, рис. 6.
Ключові слова: **урбанізація, будівельна промисловість, кабельна інфраструктура, пожежна безпека, критерії класифікації кабелів, безгалогенні композиції, силові кабелі, теплова стійкість, пожежне навантаження, сертифікована випробувальна база**.

Introduction. Three main sectors are crucial for the development of the cable industry: electric power, transport and construction. Investments in these sectors have a direct impact on the demand for cables and wires. The size of the global wire and cable market in 2022 was estimated at USD 202.05 billion. It is predicted that from 2023 to 2030 it will grow by an average of 4.2 % [1-3]. One of the main driving factors in this case is the modern trend of urbanization, which leads to the increase of cities with significantly increased requirements for electrical networks of transportation and distribution of electrical energy. This requires the development of appropriate infrastructure with significant demand for electricity in the commercial, industrial and residential sectors. Increased investments in the intelligent modernization of power transmission and distribution systems and the development of smart networks will contribute to the growth of the cable and conductor products market. So, in particular, the introduction of intelligent network technology satisfies the growing need for system-forming network connections, which leads to an increase in investments in highly efficient power underground and underwater cables of high and ultra-high voltage, including direct current [1].

According to the UN, about 60 % of the world's population will live in cities by 2030, and 68 % by 2050, which will lead not only to new network needs, but also to the renewal of aging infrastructure. Trends towards greener solutions in the transmission of electrical energy, such as e-mobility (digital), also create additional opportunities for the cable industry. In particular, renewable energy is a sector in which the demand for cable products is growing significantly. Investments in renewable energy sources contribute to growth in the segment of demand for medium voltage power cables [1, 2]. Innovations can significantly change distribution networks: cable technologies offer real solutions that turn the distribution infrastructure into an active player, for example by using the data transmission potential of power cables with integrated optical fibers. The solutions, among other things, will allow monitoring and evaluation of the network, the activity of the Internet of Things [4, 5], as well as providing detailed information about the operation of the network.

According to the mentioned trend of urbanization, the construction segment is expected to grow at the highest rate: 4.8 % in the forecast period. Thanks to the reconstruction of old commercial, residential, industrial buildings and new construction, the market for cable and conductor products is predicted to grow worldwide. This growth is split fairly evenly between civil construction, as well as the non-residential (commercial) and residential construction segments, with the latter expected to have the highest level of investment. Rapid economic development and urbanization, especially in Southeast Asia, is contributing to significant growth in construction investment. In more mature markets, such as in Europe and North America, the dynamics of growth is slower: currently the level of urbanization in Asia is 50 %, in North America is 82 %, in Africa is 43 %. For example, according to Global Construction Perspectives and Oxford Economics (British economists) [6], by 2030 it is expected that the world construction production will increase by 85 % and reach USD 15.5 trillion: China, the US and India is the top three will contribute 57 % of growth. It is expected that the US construction market will grow faster than the Chinese one in the next 15 years [7]. Thus, the growing construction sector will contribute to the global growth of the wire and cable market.

In Europe, it is predicted that the best investment forecasts are related to civil engineering projects (roads, railways, airports and seaports). These are favorable structural trends to increase the growth rate of demand for signal interlock cables and control cables. Thus, construction products of the EU are estimated at approximately EUR 500 billion. In addition, construction is one of the main European industrial sectors: it accounts for 10 % of European GDP. This domain provides 20 million jobs for more than 3 million enterprises [8]. Such a huge business needs to be kept open by the internal market of construction products in accordance with national regulations. The construction industry uses a wide range of cables with an appropriate set of electrical and mechanical properties, resistance to the influence of external climatic factors, and, first of all, must meet fire safety requirements. According to forecasts, the construction segment is projected to be the largest segment in the fire resistant cable market. Increasing construction activity stimulates the market of fire-resistant cables in the construction industry [7]. In any case, the construction sector is a factor that stimulates the growth of the wire and cable market. Trade in construction products within the EU or the European Economic Area is regulated by European rules and regulations [9-11]. The construction industry covers all design and construction activities, regardless of whether it concerns the population and private buildings, transport infrastructure, utility networks, etc. According to the Construction Products Regulation (CPR), power, telecommunication cables, data cables, control and control cables, and fiber optic cables are considered construction products in EU member states. These cables are intended for the supply of electrical energy and communication, which are permanently installed in buildings and other engineering structures [12]. Power, telecommunications, data and control cables are considered construction products, and are the only electrical products classified as construction. Cables designed for connecting appliances or for internal wiring of equipment or electrical appliances, as well as all those cables not used as cables for construction, are not included in the category of construction products. The Construction Products Regulation in the EU is mandatory for cables since July 1, 2017 [12, 13].

Eastern Europe is expected [6] to see increased growth in the construction industry over the next 15 years, as the end of the war in Ukraine requires nearly USD 1 trillion in reconstruction. A strategic task in the reconstruction of the country is the use of cable and conductor products with increased operational properties, including in the construction industry.

The goal of this work is to analyze the fire safety requirements for cables as a category of construction products and to determine the thermal resistance of power cables based on experimental thermal studies of modern electrical insulating compositions.

Problem definition and analysis of literary sources. The Construction Products Regulation establishes the agreed rules for the marketing of construction products in the EU [12]. One of the rules is that manufacturers must provide information about the safety of their products: fire safety; security for users; noise protection. All cables that fall under the category of construction products, regardless of type, are affected only by safety characteristics in case of fire (resistance and reaction to fire) and hazardous substances (emissions and content). Other technical characteristics, including electrical and mechanical, are defined in the relevant standards on the cable [14, 15]. Given that cables provide the fundamental infrastructure of today's construction sector, the strict application of state-of-the-art fire safety requirements for such infrastructure is of paramount importance for safety and reliability. The fire response of construction products in the category «Power, control and communication cables» is one of the most pressing problems in the cable industry at the moment.

Kilometers of cables laid inside the building must ensure its safety, especially during fires and emergency situations. High requirements for fire safety relate to resistance to the spread of burning when the cable is placed singly and when laid in a bundle (Fig. 1); low smoke and gas emission; low corrosive activity of gases released during cable combustion; fire resistance (preserving the performance of the cable under conditions of exposure to flame).

The fulfillment of fire safety requirements became possible thanks to a new class of materials – halogen-free compositions, which are flame-resistant polymer materials with low smoke and gas emissions that do not contain halogens [16-19]. The global market for cable polymer composites is expected to be valued at USD 13.9 billion in 2023, driven by the growing demand in the automotive, telecommunication, and construction industries [7, 10]. For the production of cables Europe accounted for 16.3 % of the global production of polymer materials in 2019 [8]. By the end of 2023, the use of fire safety cables with low smoke content and halogen-free compositions is expected to be more than 20 %. At the same time, the share of compounds based on polyvinyl chloride plasticate will decrease from 50 % to 35 % [8, 10].

a

b

Fig. 1. Fragments of the arrangement of cables in bundles inside (*a*) and on the roof of the building (*b*, cultural and entertainment center, private house, etc.)

In September 2020, the German international group HEXPOL Technologies launched a comprehensive portfolio of compounds for wires and cables based on high-performance materials, additives, advanced production technologies of organosilicon rubber and thermoplastic elastomers that meet the international cable standards IEC 60811 [20] and EN 50363 [21]. The unique fire safety characteristics of halogen-free compositions include low smoke emission, low toxicity and fire resistance and meet the requirements of RoHS (Restriction of Hazardous Substances – Directive 2002/95/EC, which limits the content of harmful substances, in particular, lead, mercury, cadmium,

The authors of [23] proved the expediency of using fire-resistant compositions for the manufacture of cable products, in which the maximum continuous temperature of the current-conducting core does not exceed 90 °C, and the maximum temperature under short-circuit conditions is 170 °C, and investigated the influence of alloying additives on the electrophysical properties of fire-resistant polymer compositions, which do not contain halogens.

The work [19] presents the composition of a halogen-free composition based on polyethylene with the introduction of flame retardants and other additives into the polymer matrix, which increase the resistance of the material to flame propagation, as well as better dispersion of fillers in the polymer. At the same time, it is emphasized that with an increase in the degree of filling of the polymer with flame retardants, its breaking strength, relative elongation, specific volumetric electrical resistance, and frost resistance decrease.

Cables are complex objects, as they consist of insulation and sheaths of polymeric materials of different chemical composition, thickness, and additives [17, 24].

Thus, on the basis of experimental studies, it was established that the characteristics of the used cable insulation material based on polyvinyl chloride plasticate (PVC) had a significant impact on the toxicity of exhaust gases. The most toxic gases are released during smoldering combustion of a cable with a plasticized PVC sheath [25].

The semi-real scale tests presented in [26] showed that the cable with polyvinyl chloride plasticate demonstrated high fire resistance properties related to heat release, smoke generation and flame propagation.

The complex fire-resistant properties of electric wires and cables are widely studied both theoretically and experimentally [17, 23, 25-27], regarding compliance with the criteria of the European classification of cables for fire safety [11], which indicates the importance of the problem.

Classification of cables by fire rating. The EU has created a single and uniform classification criterion throughout Europe to determine the fire-resistant characteristics of cables. The fire resistance classes of the cables were determined based on the classification criteria according to the amount of radiated heat in the presence of fire.

According to the effectiveness of fire propagation and heat release, 7 classes of cables are defined [28]: Aca, B1ca, B2ca, Cca, Dca, Eca, Fca (Fig. 2,*a*).

Class Aca – cables do not contribute to fire. Classes B1ca – B2ca – minimal contribution to fire. Classes Cca – Dca – Eca – combustible, contribute to fire (the contribution to the fire of cables of class E is higher than that of D). Class Fca – an undefined property contribution [29]. The classification stipulates that the manufacturer does not have requirements related to reaction to fire (the parameter «Indeterminate performance» (Euroclass) is indicated.

An additional classification concerns the release of smoke, burning drops and acidity indicators.

Smoke emission properties: s1, s1a, s1b, s2, s3 (Fig. 2,*b*). This classification provides information about the opacity of emitted smoke (s – smoke) [29]: s1 – small smoke formation and slow smoke spread; s1a – transmission coefficient of more than 80 %; s1b – transmission coefficient in the range from 80 % to 60 %; s2 – average formation and distribution of smoke; s3 – none of the above.

Burning drops/particles: d0, d1, d2 (Fig. 2,*c*). This classification provides information about the dripping of burning material during a fire (d – droplets) [29]: d0 – absence of combustible droplets or particles; d1 – absence of combustible drops or particles lasting more than 10 s; d2 – none of the above.

Acidity indicators: a1, a2, a3 (Fig. 2,*d*), for which the test described in the UNE-EN 50267-2-3 standard is additionally applied. This classification provides information on the release of acid gases under fire time (a – acidity): a1 – conductivity < 2.5 μS/mm and hydrogen pH > 4.3; a2 – conductivity < 10 μS/mm and pH > 4.3; a3 - none of the above.

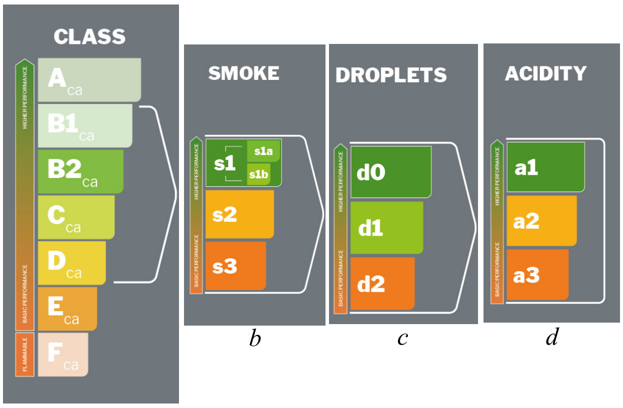


Fig. 2. Euroclassification of cables according to the category of construction products [12]

Class Aca cables are special cables with inorganic insulation tested according to [30] and must have a higher calorific potential (PCS – gross calorific potential) of less than 2 MJ/kg.

Class B1ca cables are tested according to [29] with a 30 kW flame source according to the classification criteria: flame spread FS ≤ 1.75 m, total heat release THR_{1200c} ≤ 10 MJ, peak heat release rate HRR ≤ 20 kW, higher calorific value FIGRA ≤ 120 W/s with additional classification for smoke emission, burning drops and acidity and [31] with flame spread H ≤ 425 mm.

Class B2ca cables are tested according to [29] with a 20.5 kW flame source according to classification criteria: flame spread FS ≤ 1.5 m and total heat release THR_{1200c} ≤ 15 MJ, peak heat release rate HRR ≤ 30 kW and higher calorific value FIGRA ≤ 150 W/s with additional classification for smoke emission, burning drops and acidity and [31] with flame spread H ≤ 425 mm.

Class Cca cables are tested according to [29] with a 20.5 kW flame source according to the classification criteria: flame spread FS ≤ 2 m and total heat release THR_{1200c} ≤ 30 MJ, peak heat release rate HRR ≤ 60 kW and higher calorific value FIGRA ≤ 300 W/s with additional classification by smoke emission, burning drops and acidity and [31] with flame spread H ≤ 425 mm.

Class Dca cables are tested according to [29] with a 20.5 kW flame source according to the classification criteria: total heat release THR_{1200c} ≤ 70 MJ, peak heat release rate HRR ≤ 60 kW and higher heating capacity FIGRA ≤ 300 W/s.

Class Eca cables are tested according to [31] with flame spread H ≤ 425 mm.

Class Fca cables are tested according to [31] with flame spread H > 425 mm.

The duration of the tests is 1-8 min with burner power of 1 kW with air convection [29], 20 min with burner power of 30 kW with a non-flammable shield [29] and 20 kW without a fire shield [29] with an air supply of 8000 l/min (Fig. 3).

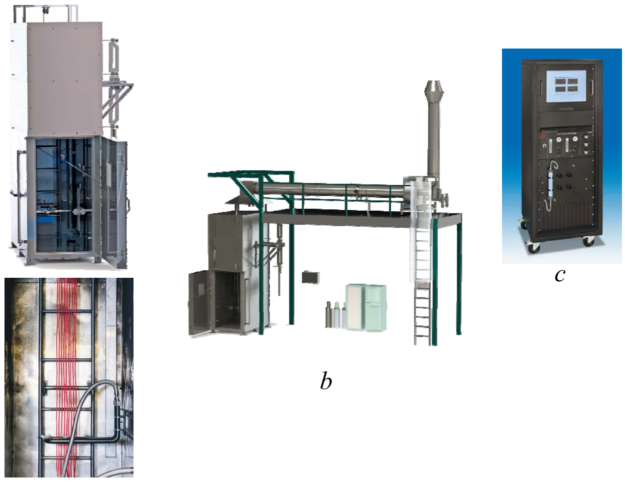


Fig. 3. Test chamber with burner and ladder with cable samples (*a*), test complex (*b*) (length 8.60 m, width 2.50 m, minimum height 4.10 m) and gas analyzer with software (*c*) [29]

Accordingly, [29] is central to cable classification tests as it combines heat release measurements (classes B1ca, B2ca, Cca, Dca), smoke penetration measurements (s1, s2, s3) and burning droplet evaluation (d0, d1, d2).

Each country has its own technical requirements and standards [32] for assessing and reducing the risk of fire consequences. High-quality cable infrastructure is a critical component of the construction industry and must meet fire safety requirements to ensure continuity of power and communication to all critical devices in the event of a fire. The performance of the cables itself during a fire is of crucial importance. The release of cables in the category of construction products requires an understanding by all involved parties of the importance of providing the construction industry of Ukraine with cable and conductor products by domestic manufacturers.

In accordance with the current building regulations of public buildings, it is necessary to take into account the established limit values for the accumulation of combustible materials located directly in public buildings, including cables and wires. There is a need to determine the thermal resistance of cables and the amount of heat released during their burning, i.e. fire load.

Determination of thermal resistance and fire load of power cables with modern electrical insulating compositions. The cable business is largely focused on the use of modern polymer compositions with the appropriate set of physico-chemical, electrical and thermal properties with cable manufacturing technology adapted to their rheological indicators as a whole. The implementation of fire safety requirements is related to reaching a certain compromise between the level of requirements for fire safety indicators and the main electrical and physical-mechanical characteristics of cables [33-35]. Significant efforts and investments in innovation and certification of cable and conductor products require manufacturers to create construction products of the «Power, control and communication cables» category with a high level of fire safety in accordance with the euroclassification of cables in terms of reaction to fire depending on the level of safety. Fire safety features in cable designs can be implemented individually or in combination.

The degree of realization of fire safety requirements of cables is determined by the scope of their application.

Scientifically based decisions on the fire resistance of cables to confirm the appropriate classification [12, 29] are made on the basis of tests of cable samples in specialized certification centers (laboratories). Such tests are expensive. So, for example, 12 cable samples [33] are needed to confirm the reaction to fire class B2ca, which costs more than EUR 18,000.

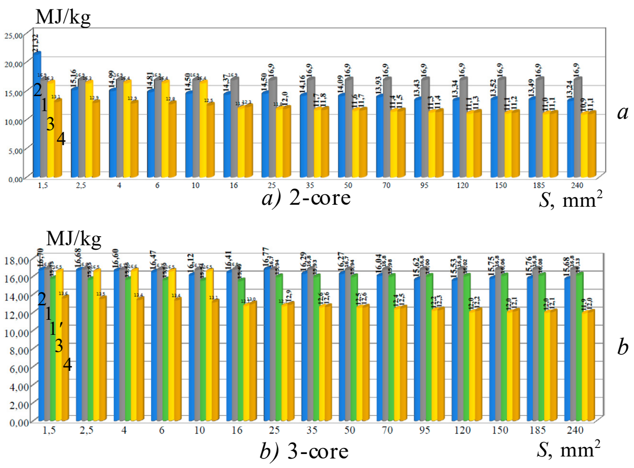
Determining the thermal resistance of cables on the basis of the obtained experimental data on the thermal resistance of the actual polymer materials of the cable, depending on the design and field of application, is necessary and justified. Especially – at the stage of mastering and determining the prospects for the production of cables with modern halogen-free electrical insulating materials in accordance with fire safety requirements. For example, cables for internal laying in residential and industrial construction must meet European requirements for electrical safety and load capacity. Instead of 2-core installation wires, 3-core (phase, neutral, grounding) ones are needed for residential buildings, offices, and work spaces. Instead of 4-core cables, which are currently used to supply electricity, for example, to residential buildings from substations, 5-core cables are needed. Of course, such cables must meet fire safety requirements.

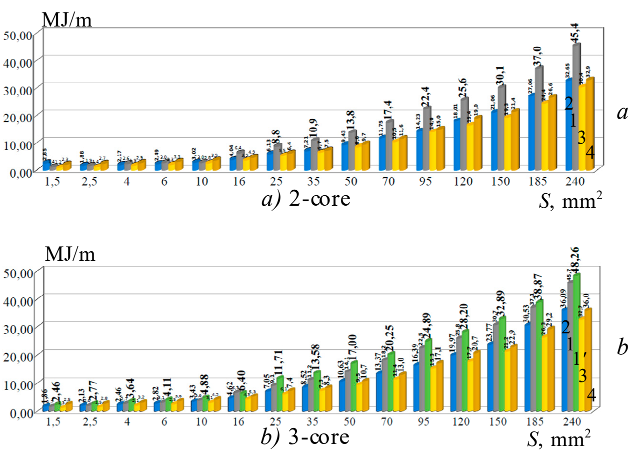
The calorific value of cross-linked polyethylene is 48 MJ/kg, self-extinguishing polyethylene is 41.9 MJ/kg. For polyvinyl chloride plastic, this depends on the brand (recipe), MJ/kg: ordinary recipes – 23.7 (insulating) and 25.8 (sheathing); reduced flammability 18.4 – 19.7; reduced fire safety with low smoke and gas emission 10 (for filling) – 17.7 (for sheath) – 18.9 (for insulation) [36-38]. For example, 1 m of cable with polyvinyl chloride insulation in a protective sheath made of polyvinyl chloride plastic (bare) VVG 4×35+1×16 releases during combustion 10.5 MJ of heat; the VVHng cable 4×35+1×16 – 9.9 MJ, and the VVHng-LS cable – 9 MJ [39].

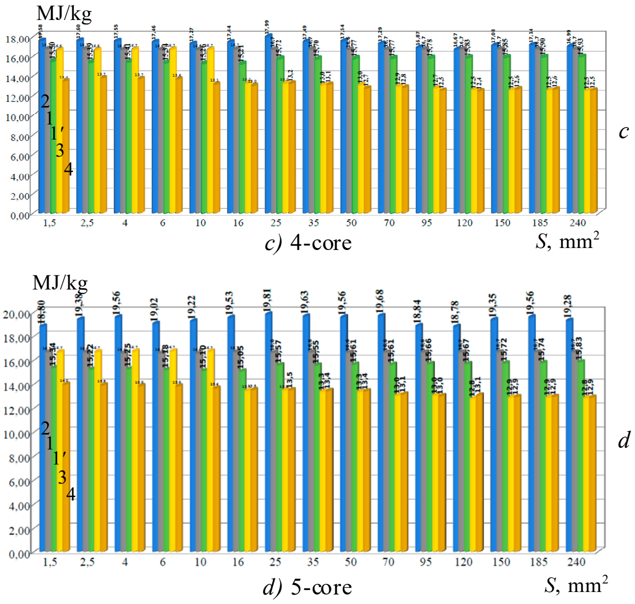
In non-flammable ng (non-flammable) and ng-LS (non-flammable with low smoke) cables, the flammability of the sheaths is reduced due to the introduction of flame retardants (aluminum oxide trihydrate, magnesium hydroxide). And although the flammability of the materials has decreased somewhat, these compositions continue to remain combustible materials and will burn in the event of a fire, releasing smoke and a large amount of heat into the surrounding space [39, 40].

Power cables with copper cores at voltage of 0.6/1 kV and frequency of 50 Hz for the transmission and distribution of electrical energy in stationary installations, insulation, inter-core filling and sheath made on the basis of modern polymer materials, including halogen-free compositions, were considered. Cables provide the transmission of electrical energy, control signals and control of electrical equipment, the operation of which in case of fire is mandatory for rescue operations. They are used at facilities with increased fire safety requirements for single and laid cable bundles in rooms and tunnels.

Figures 4, 5 present, depending on the number of cores of different cross-sections, the determined values of thermal resistance and thermal load of power cables on the basis of conducted experimental studies of the thermal resistance of insulation materials, between the core filling and the polymer sheath, removed from the cable samples.







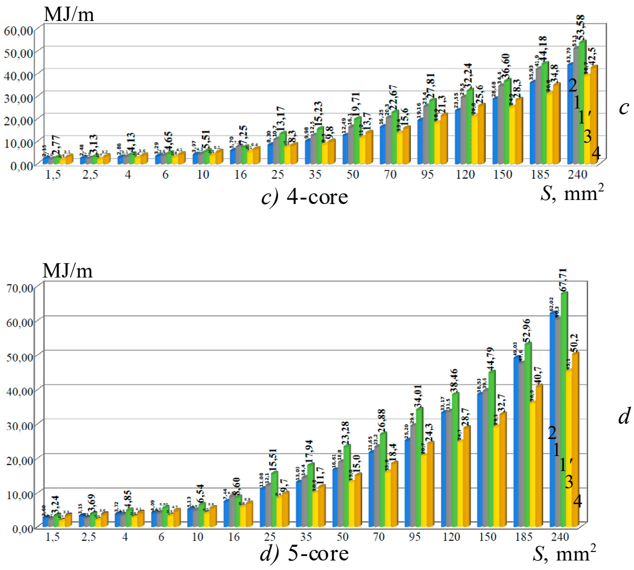


Fig. 4. Thermal resistance of power cables depending on used materials and design

Fig. 5. Fire load of power cables depending on the used materials and design

Figure 6 shows the correlation dependence of the ratio of thermal resistance (p.u.T) and fire load (p.u.F) of 5-core vs 3-core cables with different applied polymer compositions (notation in Fig. 6 is identical to that shown in Fig. 4, 5, respectively).

Curves in Fig. 4–6 correspond to: 1, 1' – compositions containing halogens; 2, 3 and 4 – halogen-free.

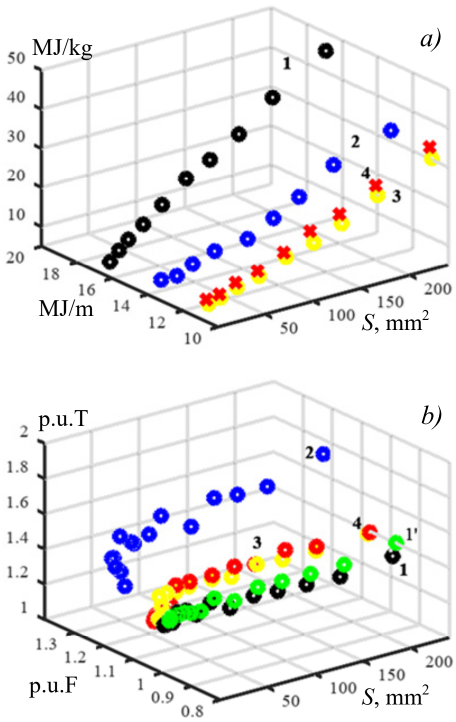


Fig. 6. Correlation between heat resistance and fire load for 2-cores (*a*) and ratio of these parameters of 5-core vs 3-core (*b*) power cables with different applied polymeric materials

When the cross-section of the current-conducting core increases, depending on their number, there is a change in the thermal resistance and fire load of the cables. For example, for a 2-core cable, the thermal resistance and fire load of a halogen-containing polymer composition (curve 1, Fig. 4,*a* and Fig. 5,*a*) is lower compared to a halogen-free one (curve 2, Fig. 4,*a* and Fig. 5,*a*) in the case of smaller values of the cross-section of the current-conducting core. And vice versa, it increases and exceeds these indicators in the case of larger cross-sections of the cable core. Such dynamics are also observed for 3-, 4-, and 5-core cables (compare curves 1 with curves 2, 3 and 4 in Fig. 4–6). In other words, the effectiveness of halogen-free compositions to meet fire safety requirements increases with the increase in cross-section and the number of cores in the cable.

Thus, the fire safety of cables is determined by the applied cable compositions and significantly depends on the design of the cables: the diameter of the current-conducting core and their number, that is, the ratio between the metal and polymer parts in the cable.

Conclusions.

1. Generalized requirements for fire safety of cables in the construction sector according to the category «Power, control cables and communication cables» are defined.
2. The classification of cables according to the fire sign in accordance with the EU Construction Products Regulation with the relevant classification criteria and test methods for determining the fire-resistant characteristics of cables is given.
3. A comparative analysis of fire safety indicators is presented based on the determination of thermal resistance and fire load depending on the applied composite polymer compositions and the design of low-voltage power cables.
4. Based on the correlation analysis between thermal resistance and fire load, which are important parameters for confirming the quality and fire safety of the entire cable, the effectiveness of the use of halogen-free polymer compositions in power cables with a larger cross-section and number of cores has been confirmed.

Conflict of interest. The authors declare no conflict of interest.

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