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FIRE PROPERTIES OF ELECTRIC CABLES USED IN BUILDINGS

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Summary

A significant number of cables of different materials and construction is used extensively in building objects increasing their fire load and, therefore, strongly influencing safety in the case of fire. Electric cables and electrical installations constructed from them, despite being important elements of fire safety, are not considered in the general analysis of the fire safety of buildings and are usually not assessed as potential fire risks. One of the tasks in the field of counteracting fire hazards in buildings should be to reduce the risk of fires caused by short circuits in electrical installations. In the event of fire, the process of fire propagation involving electric cables should be considered, which, due to the way cables are installed in buildings, can transfer fire over long distances from the origin of the fire and across storeys through installation shafts.

The scientific problem of the doctoral dissertation is to determine the impact of significant constructional and material parameters of electric cables on their fire properties by establishing the qualitative, and possibly also quantitative, relationships between these parameters.

The aim of the presented work was to investigate the effect of material and constructional parameters on the fire properties of electrical cables, such as heat release, smoke generation, range of flame spread and amount of toxic fire effluents under various ventilation conditions. To the best of the author's knowledge, such systematic research has not been published so far. The presented study is original and fills the scientific gap regarding the constructional and material parameters of electric wires and cables, which influence their fire properties.

In order to investigate the relationship between the constructional–material parameters of cables and their fire properties, eighty-three cables (eighty-nine cable samples) were examined by means of a standard experimental method. The selection of cable samples included the presence of one distinctive parameter. The conclusions drawn from the experiments were as follows: (1) construction, the number of conductors and the presence of armour or concentric metallic conductors improve fire properties by forming a barrier against flame penetration through the cable; (2) the use of copper conductors resulted in decreasing fire parameters compared to cables with aluminium conductors (maximum average heat release rate parameter al-

most four times lower for copper cables); (3) construction materials based on plasticised poly(vinyl chloride) significantly reduce the fire properties of cables compared to halogen-free materials (maximum average heat release rate parameter more than 17 times higher for fully halogenated cables), which is due to the decomposition process of the material; (4) no clear relationship between the fire parameters and cable parameter χ was found. The χ parameter was developed to improve the monotonicity of the reaction to the fire test results obtained and has been used in the selection of cable samples for testing within the same cable family so far.

As the investigation showed a significant impact of the number of metallic barriers (conductors) on flame penetration into the inner layers of electric cables and the volume of non-metallic materials on the fire properties of cables, a parameter related to the volume of effective non-combustible content Ω was proposed. The new Ω parameter depends on the non-metallic non-combustible components volume to non-metallic combustible components volume ratio and the effective area of heat transfer within the cable. Increasing Spearman's correlation factors (close to −1) were obtained for total heat release rate and total smoke generation parameters as a function of the Ω parameter rather than the χ parameter.

In order to examine the amount of fire/combustion gases under ventilation-controlled fires, a simple poly(vinyl chloride)-based copper electric wire widely used in buildings was studied by means of a Steady State Tube Furnace. A reference pure polymer unplasticised poly(vinyl chloride) and additionally pure low-density polyethylene were also tested. Decreasing carbon dioxide yields at different ventilation conditions for the poly(vinyl chloride) based copper electric wire were obtained in comparison to three times higher yields for pure poly(vinyl chloride) and two times for low-density polyethylene than those received for the tested wire at the same ventilation conditions, which confirms the insignificant contribution of the hyperventilation effect to humans during a cable fire. To the contrary, four times higher values of toxic carbon monoxide yields were obtained for the tested wire rather than for the reference polymer and pure low-density polyethylene. The maximum value of carbon monoxide yield (0.57 g/g) was obtained in the case of 5 l/min of primary airflow, which decreased with increasing ventilation. The measured yields of hydrocarbons were similar to the reference values except for the equivalence ratio $\phi = 0.27$. The corrosive and toxic hydrochloric acid occurring in fire effluents from the studied wire was independent of the ventilation conditions tested. The reaction between copper and the hydrochloric acid compound, inorganic fillers, and hydrochloric acid decreased the hydrochloric acid content in fire effluents.

Analysis using Quintiere's theory showed that the cone calorimeter method can be used in numerical modelling of the cable burning process, and its use can significantly facilitate and reduce the number of cable fire tests, without adversely affecting the final results.

Summarising, the analysis of the impact of cable construction is an important element from the point of view of the fire safety of buildings. In the course of the study, it was found that factors such as the shape, number and material used for conductor formulation, as well as the types of materials from which the non-metallic elements of the cables are made, and the presence of armour or concentric conductors significantly influence the fire properties of cables, such as heat release, smoke generation, range of fire spread and fire effluent toxicity, largely reducing the fire properties of cables. The experiments enabled the development of a new cable parameter Ω, which is a better predictive indicator of cable flammability than the standard and commonly used parameter χ. In addition, it was found that it is possible to replace large geometric scale fire tests with a simpler cone calorimeter method by applying Quintiere's theory of electric cables.

FROM THE AUTHOR

Fire safety is multidisciplinary in nature and combines scientific disciplines such as physics, chemistry, mechanics as well as modelling and numerical simulation. The increasing use of electrically powered equipment is driving the demand for sophisticated designs and materials used to construct the electrical cables that power these devices. Consequently, under fire conditions, cables contribute a significant fire load and are involved in the spread of fire throughout a building. This monograph is based on the author's doctoral dissertation [5], in English, considering the reviewers' comments and questions raised during the public defense.

The issues addressed therein are primarily concerned with the proper selection of electrical cables in terms of their fire performance. A meticulous analysis of the influence of design and material parameters on the behaviour of electrical cables under fire conditions was carried out on a large number of electrical cables commonly manufactured and used in Europe. A novel concept of an empirical parameter Ω, related to the effective volume of non-metallic elements, the volume of combustible non-metallic elements of cables and the effective heat transfer surface area, was also proposed.

I would like to express my sincere gratitude to dr hab. inż. Jadwiga Fangrat, Professor at Building Research Institute, for valuable advice given during the preparation of the dissertation and for her kindness and understanding, as well as to the reviewers of the monography – Senior Brigadier dr hab. Marzena Półka, Professor at the Main School of Fire Service, and dr. hab. Andrzej Plichta, Professor at the Warsaw University of Technology, for their insightful reviews, which undoubtedly contributed to raising the substantive quality of the monograph. I would also like to express my gratitude to the Management of the Building Research Institute for their support in conducting the fire testing of electrical cables, as well as to the team of the Building Research Institute Library for their assistance in completing the scientific literature. I would like to thank the management and my colleagues from the Fire Research Department for their kind support of my work and inspiring discussions.

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Katarzyna Kaczorek-Chrobak

1. INTRODUCTION

World statistics indicate that 37.3% of fires in 2017 occurred in residential buildings. In the same year, the highest number of fire deaths occurred in the following countries: Russia, Belarus, Latvia, Ukraine, Lithuania and Estonia, and this trend does not seem to be shifting. In Poland, 475 fire victims were registered in 2017 [6]. In 2019, about 153,500 fires were recorded in Poland, including almost 38,000 in public and residential buildings, factories and warehouses (Fig. 1), where 507 deaths occurred [7].

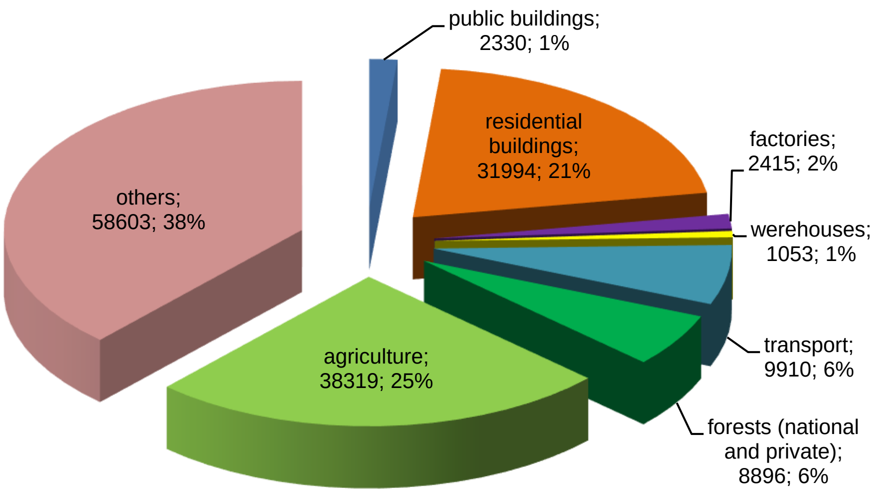

Fig. 1. Number of fires in Poland in 2019 in terms of type of object [7]

Any fire that breaks out in a building is of an exceptional, destructive nature [8]. When the fire occurs, the following changes in the environment take place:

– thermal conditions,
– pressure,
– chemical composition of air in the fire zone (hyperventilation and toxic products generation),
– smoke obscuration [9].

In accordance with the 'Technical conditions to be met by buildings and their location' [10], buildings are divided into appropriate fire resistance classes. Those classes are ordered from the highest (A) to the lowest (E). The fire threat to people class (ZL) refers to residential, multi-occupancy and public buildings. The choice of these classes depends on the size of the building, the number of floors and the number of people staying in the building at any one time.

Construction products are evaluated for their fire safety. These include mainly properties related to the fire resistance of buildings and the reaction to fire of the building materials used in the buildings.

The term "fire resistance" denotes the 'ability of an element of building construction, component or structure to fulfil, for a stated period of time, the required stability, fire integrity and/or thermal insulation and/or other expected duty in a standard fire resistance test', whereas the term "reaction to fire" refers to the 'response of a material under specified test conditions contributing to a fire to which it is exposed' [11].

Nowadays, fire protection is aimed at minimising the risk of a fire in order to protect life and property. The construction of high-rise buildings, skyscrapers and large space warehouses has led to new challenges in the field of fire safety, especially in the case of fire toxicity [12], whose indispensable foundations are chemical processes generally included in fire chemistry.

Some electrical products, such as insulated cables and installation pipes may, in practice, occupy large areas of building structures and their finishing materials, or may pass through firewalls. In such cases, electrical products exposed to an external fire should be assessed from the point of view of their contribution to the fire hazard, compared to the contribution of construction materials or of a structure without electrical installations.

In general, each fire is a serious environmental issue, but cable fires create additional damage to the environment, as 90% of wires and cables contain halogen due to technological (e.g. simple construction) and financial (low cost) purposes [13]. In the case of the fire behaviour of cables commonly used in buildings, a number of different cables divided into cable families have been examined [14, 15].

The risk of fire has to be considered for each electrical installation when designing the component circuit and device, and when selecting the material in order to reduce the probability of a fire, due to unpredictable or abnormal use, faulty operation, or damage. The main goal of fire protection is to prevent an ignition originating in the part supplied with electrical power, and when an ignition does occur, to restrict the fire within the limits of the electrical equipment. In case the surfaces of electrical products are exposed to external fire, it is necessary to ensure that they do not contribute to further fire spread more than the construction materials and structures in their vicinity.

The fire hazard presented by electrical equipment depends on its properties, operational conditions and on the properties of its environment. This is why the fire hazard assessment procedure should specify the description of the product, and the conditions of its operation and its environment. These are all elements of the process of evaluation of construction products in terms of fire safety according to the CEN procedures based on [16] (Fig. 2).

The first stage – fire scenario – is the most important, because it answers the following question: what is the type of fire to be considered? The answer allows for the designing of a new experimental method or the use of an existing one to test the product or element.

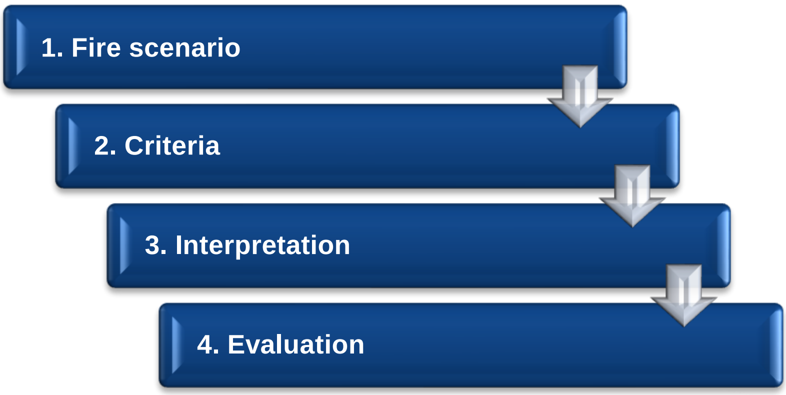

Fig. 2. Process of evaluation of construction products in terms of fire safety according to CEN procedures based on [16, 17]

The second stage – criteria – defines the evaluation criteria (limits) of fire safety measures in order to compare the behaviour of different products under the defined conditions of the chosen fire scenario in stage (1). Then, the evaluation limits can be established in terms of: (a) Health and life safety, and (b) Loss of property. Indirect methods are also very useful at this stage.

The third stage is the interpretation of the test results obtained during the experimental and indirect methods of analysis performed in stage (2), leading to the fourth stage (4), which is the evaluation through an assigned class (e.g. euro class).

In the cited doctoral dissertation [5] the properties of materials subjected to high (fire) temperatures are referred to as “fire properties” which is often used in scientific articles and monographs [18, 19, 20, 21] by analogies to commonly used terms “mechanical properties”, “chemical properties”, “physical properties”. On the other hand, the term “fire performance” is in use when addressing the cable fire behaviour in large-scale standard experiments [2, 16, 17, 22, 23, 24, 25]. In this monography the term “fire properties” is used in more general meaning then “fire performance”. This approach was based of the example of Hirschler, who stated [19] ‘The fire properties addressed include ignitability, ease of extinction (oxygen index), flame spread (small scale and intermediate scale), heat release, smoke obscuration, smoke toxicity, hydrogen chloride emission and decay, and performance in real-scale fires.’

In terms of fire chemistry, the basic fire scenarios are classified into various types: non-flaming/smouldering combustion, well-ventilated flaming fires and early/ventilation-controlled (vitiated) flaming fires (Tab. 1) [26, 27]. This evaluation is important in terms of the release of toxic combustion products from electric cables.

Smouldering/non-flaming fires involve slow thermal decomposition without flames. The thermal decomposition process may be induced by heat supplied externally or it may be self-sustaining. Products are very rich in inorganic acids, carbon monoxide (CO) and organic compounds, which are usually highly irritating to the respiratory tract [28, 29].

Table 1. Evaluation of standard fire types [30]

	Heat [kW m^{-2}]	Max temp. [°C]		Oxygen [%]		Equivalence ratio ϕ	$\frac{V_{CO}}{V_{CO_2}}$	Combustion Efficiency [%]
		fuel	smoke	in	out			
Non-flaming								
1a. Self-sustained smouldering	n.a.	450 to 800	25 to 85	20	0 to 20	–	0.1 to 1	50 to 90
1b. Oxidative, external radiation	–	300 to 600	–	20	20	< 1	–	–
1c. Anaerobic external radiation	–	100 to 500	–	0	0	>> 1	–	–

	Heat [kW m^{-2}]	Max temp. [°C]		Oxygen [%]		Equi-valence ratio ϕ	$\frac{V_{CO}}{V_{CO_2}}$	Combustion Efficiency [%]
		fuel	smoke	in	out			
Well-ventilated flaming								
2. Well--ventilated flaming	0 to 60	350 to 650	50 to 500	~20	0 to 20	< 1	< 0.05	> 95
Under-ventilated flaming								
3a. Low ventilation room fire	0 to 30	300 to 600	50 to 500	15 to 20	5 to 10	> 1	0.2 to 0.4	70 to 80
3b. Post--flashover	50 to 150	350 to 650	> 600	< 15	< 5	> 1	0.1 to 0.4	70 to 90

Well-ventilated flaming fires occur at the beginning of a fire, when there is plenty of air available. The equivalence ratio ϕ (1) [31, 32], which is used for the characterisation of ventilation conditions in terms of fire, is relatively low (less than 1) [33]. Typically, for well-ventilated fires, ϕ is less than 0.7 [31].

$$\phi = \frac{\text{actual fuel} - \text{to} - \text{air ratio}}{\text{stoichiometric fuel} - \text{to} - \text{air ratio}} \tag{1}$$

Under these conditions combustion is most efficient. The main products obtained during decomposition are carbon dioxide (CO_2), water and heat. The yield of smoke and toxic products initially tends to be low [28].

When the air supply is restricted compared to the fuel available for combustion, ventilation-controlled flaming fires occur. They may consist of pre-flashover fires in enclosed spaces or large post-flashover fires, where all surfaces are ignited in high temperature (often 450 – 1200°C) conflagrations in very large or ventilated spaces. Therefore, ventilation--controlled fires tend to be the worst for toxicity, because they produce large amounts of effluent containing high yields of toxic products, for instance: CO, CO_2, HCN, organic products, and a lot of smoke and inorganic acid gases [28].

The main cause of injury and death in fires is incapacitation resulting from exposure to fire effluents. In Poland, such a dataset is lacking. It has been mentioned, however, that statistically 60 – 80% of fire victims have been affected by fire effluents inhalation during a fire [34].