Article

Influence of Constructional-Material Parameters on the Fire Properties of Electric Cables

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Abstract: The significant number of cables of different materials and construction used extensively in building objects increases their fire load and, therefore, strongly influences safety in the case of fire. The purpose of the study was to identify relevant factors related to the construction of electrical cables, and perform a qualitative and quantitative assessment of their influence on specific fire properties, such as heat release and smoke production. Fifteen cables of different construction and materials were studied using the EN 50399 standard test. The analysis was focused on cable constructional-material parameters related to the chemical composition of non-metallic elements and the number and shape of conductors in the cable, as well as the concentric barrier as armor or the copper concentric conductor. The conclusions drawn from the experiments were: (1) Construction, the number of conductors, and the presence of armor or concentric metallic conductors improve the fire properties by forming a barrier against flame penetration through the cable; (2) the use of copper conductors resulted in a decrease of fire parameters compared to cables with aluminum conductors (peak HRR parameter even four times lower for copper cable); (3) construction material based on non-plasticized poly(vinyl chloride) (PVC) significantly reduced the fire properties of cables more than halogen-free materials (LS0H) (peak HRR parameter more than 17 times higher for the fully halogenated cable), which is due to the decomposition process of the material; and (4) no clear relationship between the fire parameters and the cable parameter, χ, was found.

Keywords: construction of electric cables; reaction to fire of electric cables; fire safety of buildings

1. Introduction

The large number of cables present in buildings strongly increases their fire load and facilitates the spread of flames over a long distance (both horizontal and vertical) in the case of fire. Cables can be relatively easily self-ignited internally by a short circuit in the installation or ignited from an external burning source [1–3]. Based on the end-use application, cables can be divided into groups, as follows: Power, telecommunication, electromagnetic, control, network, and optical cables [4]. A major problem is the selection of cables based on their fire properties.

A number of experimental studies using various laboratory tests were performed and physical-based theories were proposed to describe the fire performance of electric wires and cables. The authors of the most recently published review on electric cables declared: “The complex role of the core, specifically whether it is a heat source or heat sink, in the ignition, flame spread, burning, and extinction, has been emphasized throughout this review.” They conclude that, “a deeper understanding of fire phenomena in real wire and cable is still quite challenging, and attempted inferences for real wire fires based on the qualitative or semi-empirical analysis of limited laboratory data are not yet convincing enough [...] there is still a large gap between the fundamental research using laboratory wires and applied research using commercial wires” [3]. Electric wires were tested separately or in cable trays. The flame spread and fire growth were shown to be predictable using a fire spread and
growth (FSG) model developed at Factory Mutual Research Corporation (FMRC) and small-scale flammability measurements for polyethylene/poly(vinyl chloride) PE/PVC cable [5]. The authors of other work stated that “a simple and systematic way to rank the fire performance of insulated electrical cables [...] is particularly significant because of the complexity of the cables tested—the cables have insulations of different compositions and interactions between the conductor and the insulation affect the fire performance.” [6].

The complex internal structure of cable was found to cause difficulties in investigation of the pyrolysis and combustion behavior of cable sheath by using the popular experimental method, cone calorimeter method, and full-scale experiments [7]. Cables presenting non-planar surfaces show significantly different heat flux levels during cone calorimeter tests [8]. It was also previously found that the time for ignition is only dependent on heat flux while the influence of the sheath is that it delays the occurrence of the main peak of the heat release rate corresponding to the decomposition of non-flame retarded cable insulations [9]. However, in many cases, cone calorimeter equipment becomes a relevant method for estimating the full-scale fire behavior of various products [10], such as cables.

In the case of the reaction to fire properties of cables, which are commonly used in buildings, a number of different cables grouped in cable families were tested, especially for CE marking [11] under the Construction Product Directive [12].

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., easy molding) and financial (low cost) reasons. An earlier work has shown that there is a relationship between the number of conductors and the fire properties of electric power cables, which does not present a direct relation between the deterioration of fire properties and the increase of non-metallic content in cable construction [1].

Electric cables consist of metallic (copper or aluminum) conductors and optionally concentric conductors (copper or aluminum), steel armor, or screens [13]. Cable insulations, outer sheath, and, optionally, bedding or various separators and tapes are built of combustible synthetic materials [14–17]. The volume of tapes is less than 1% of all the non-metallic elements of the cables and those elements do not significantly influence their fire properties.

The fire properties of each cable are expressed as the so-called cable parameter, \( \chi \) (1) [1,18]. The cable parameter was invented to predict the monotonical trend of fire parameters obtained during the EN 50399 standard test of cables within the same cable family [19]:

\[
\chi = \frac{c}{d^2} V_{\text{combust}}
\]

where \( \chi \) is the cable parameter; \( c \) is the number of conductors; \( V_{\text{combust}} \) is the non-metallic volume of combustible cable components, \( m^3/1m \) bunched cable according to EN 50399 [20]; and \( d \) is the diameter of the cable, m.

According to the above Equation (1), the cable parameter, \( \chi \) is directly proportionate to the number of conductors \( c \) and the non-metallic volume of combustible cable components in 1 m of bunched cable \( (V_{\text{combust}}) \). It is inversely proportional to the square of the diameter of the cable \( (d^2) \).

The cable parameter has been shown to be more complex than the simple cable diameter \( d \) and non-metallic volume \( (V_{\text{combust}}) \) in the case of selecting cable samples for testing within the identified cable family [19].

2. Research Problem

Unlike most of the earlier studies published so far, the motivation for the presented work was not to design another experimental method, but to investigate the effect of material and constructional parameters on the fire behavior of electrical cables in a systematic way. To the best of the author’s knowledge, such systematic research has not been published so far. This signifies a research gap and therefore the presented study is original.
Under fire conditions and easy oxidation, a large amount of heat and smoke is produced. Electric cables may present different behaviors under the same fire conditions. The main aim of the study was to identify the relevant factors related to the construction and content of electrical cables and provide a qualitative and quantitative assessment of their influence on the specific fire properties of these building products.

Five major groups of constructional-material parameters concerning cables were chosen for the analysis (Figure 1).

The fire behavior of cables was described by a number of standard parameters, such as maximum heat release rate (peakHRR$_{av}$, kW), total heat release (THR$_{1200s}$, MJ), maximum smoke production rate (peakSPR$_{av}$, m$^2$/s), total smoke production (TSP$_{1200s}$, m$^2$), flaming droplets, and particles and toxic product yields, as measured under standardized conditions.

3. Materials and Methods

Fifteen different cables were chosen for testing (Table 1). Representative cables with specific parameters were selected, differing in:

- Construction materials of conductors (specimens No 1, 2, 3, and 4);
- Conductor cross-section (specimens No 12, 13, 14, and 15);
- Non-metallic materials of cables (specimens No 5, 6, 7, and 8); and
- Armor and concentric conductors’ occurrence (specimens No 8, 9, 10, and 11).
Table 1. Characteristics of the cable specimens.

| Specimen No | Conductor Size | $\chi$  | Conductor Material/Shape | Outer Sheath | Armor or Concentric Conductor | Bedding | Insulation |
|-------------|----------------|--------|--------------------------|--------------|-------------------------------|---------|------------|
| 1           | $4 \times 35$ mm$^2$ | 3.93   | Cu/sector                | LS0H compound | Cu tape and wires             | LS0H tape | XLPE       |
| 2           | $3 \times 300$ mm$^2$ | 11.69  | Cu/sector                | LS0H compound | Cu tape and wires             | LS0H tape | XLPE       |
| 3           | $4 \times 35$ mm$^2$ | 4.06   | Al/sector                | LS0H compound | Cu tape and wires             | LS0H tape | XLPE       |
| 4           | $3 \times 300$ mm$^2$ | 11.69  | Al/sector                | LS0H compound | Cu tape and wires             | LS0H tape | XLPE       |
| 5           | $3 \times 1.5$ mm$^2$ | 32.32  | Cu/round                 | PVC compound  | –                             | EPDM     | PVC        |
| 6           | $3 \times 1.5$ mm$^2$ | 32.25  | Cu/round                 | PVC compound  | –                             | EPDM     | XLPE       |
| 7           | $3 \times 1.5$ mm$^2$ | 40.62  | Cu/round                 | LS0H compound | –                             | EPDM     | XLPE       |
| 8           | $3 \times 1.5$ mm$^2$ | 26.41  | Cu/round                 | EVA/ATH/ZnB  | –                             | XLPE     | silane XLPO|
| 9           | $2 \times 16$ mm$^2$ | 10.71  | Cu/round                 | thermoplastic LS0H | – | LS0H compound | XLPE |
| 10          | $3 \times 1.5$ mm$^2$ | 19.93  | Cu/round                 | EVA/ATH/ZnB  | Cu tape and wires             | XLPE     | silane XLPO|
| 11          | $2 \times 16$ mm$^2$ | 8.09   | Cu/round                 | thermoplastic LS0H | Galvanized steel wires | LS0H compound | XLPE |
| 12          | $3 \times 300$ mm$^2$ | 3.97   | Cu/round                 | LS0H compound | Cu tape and wires             | LS0H compound | XLPE |
| 13          | $4 \times 25$ mm$^2$ | 9.65   | Cu/round                 | thermoplastic LS0H | Galvanized steel wires | LS0H compound | XLPE |
| 14          | $3 \times 300$ mm$^2$ | 4.5    | Cu/sector                | LS0H compound | Cu tape and wires             | LS0H compound | XLPE |
| 15          | $4 \times 25$ mm$^2$ | 10.78  | Cu/sector                | thermoplastic LS0H | Galvanized steel wires | LS0H compound | XLPE |
The experiments were conducted by means of a standardized large geometric-scale test apparatus \cite{20,21} (Figure 2).

![Figure 2. External view of EN 50399 standard test chamber at the ITB Fire Testing Laboratory in Pionki, Poland.](image)

Cables were tested inside the chamber, in their end-use application as cable trays mounted on a 4-m long ladder (Figure 3a). The burner nominal heat release rate (HRR) level of 20.5 kW, airflow rate through the chamber of $8000 \pm 800 \text{ L/min}$, and a white light detector were used \cite{20}.

Cable specimens of the size of about $3.6 \pm 0.1 \text{ m (height)} \times 300 \text{ mm (width)}$ were ignited from the front side by the burner; initially, most heat was emitted from the front side of a specimen \cite{22}. Carbon dioxide concentration and oxygen depletion were measured using non-dispersive infrared (NDIR) spectrometers. A single test of each cable was performed according to the EN 50399 standard, but during each experiment, the specimen consisted of several pieces of the studied cable (the exact number depended on the cable diameter as the specimen width was constant and did not exceed 300 mm) were tested. In conclusion, several pieces of each cable were studied during a single experiment.
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Figure 3. Cable specimen No 9 installed on the test ladder (a) before the test (b) after the test at the ITB Fire Testing Laboratory in Pionki, Poland.

4. Results and Discussion

Each cable specimen was tested once, and the heat release and smoke production results are presented in Figure 4.

The summary chart (Figure 4) shows that there is no clear relationship shown between the fire parameters and cable parameter \( \chi \). Relatively low values of fire parameters were obtained for cables with values of the cable parameter, \( \chi \), below 26.41, which is in good agreement with the results obtained within a large round robin project, the so-called FIPEC project [23] and CEMAC project [11].

The maximum values of peak\( \text{HRR}_{\text{av}} \), THR 1200s, peak\( \text{SPR}_{\text{av}} \), and TSP 1200s were obtained for specimen Nos 5 and 6, but the highest level of each parameter (peak\( \text{HRR}_{\text{av}} = 229 \) kW, THR 1200s = 67 MJ, TSP 1200s = 155 m², and peak\( \text{SPR}_{\text{av}} = 0.48 \) m²/s) was obtained for cable No 5, consisting of a PVC-based outer sheath and insulations and non-vulcanized rubber (EPDM) as a bedding (Table 1), even if the highest value of the cable parameter (equal to 40.62) was calculated for unarmored non-halogenated cable No 7 (Table 1). Lower values of the fire parameters were obtained for non-halogenated cables with various construction parameters. The discussion of this behavior is provided below in Section 4.4.

The repeatability and reproducibility of the EN 50399 test method were shown to be sufficient for the cable test example (Table 2).

Table 2. Repeatability and reproducibility of the EN 50399 test method

| Specimen No. | peak\( \text{HRR}_{\text{av}} \), kW | THR 1200s, MJ | TSP 1200s, m² | peak\( \text{SPR}_{\text{av}} \), m²/s |
|--------------|---------------------------------|---------------|---------------|-------------------------------|
| 1            | 355                             | 125           | 204           | 1.06                          |
| 2            | 322                             | 117           | 228           | 1.04                          |
| 3            | 327                             | 117           | 203           | 0.91                          |

Coefficient of variation, % 4.3 3.0 6.6 5.5

Each specimen according to EN 50399 consists of a number of cable pieces mounted on the test ladder. Three specimens from the same eight-core non-halogenated cable (but other than those taken for main study) were tested to show the repeatability and reproducibility of the test method. Whole
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The maximum values of peakHRR_{av}, THR_{1200s}, peakSPR_{av}, and TSP_{1200s} were obtained for specimen Nos 5 and 6, but the highest level of each parameter (peakHRR_{av} = 229 kW, THR_{1200s} = 67 MJ, TSP_{1200s} = 155 m², and peakSPR_{av} = 0.48 m²/s) was obtained for cable No 5, consisting of a PVC-based outer sheath and insulations and non-vulcanized rubber (EPDM) as a bedding (Table 1), even if the highest value of the cable parameter (equal to 40.62) was calculated for unarmored non-halogenated cable No 7 (Table 1). Lower values of the fire parameters were obtained for non-halogenated cables with various construction parameters. The discussion of this behavior is provided below in Section 4.4.

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The coefficient of variation was calculated as the ratio of the standard deviation to the mean value of the results. It is relatively low for each fire parameter of the three specimens (Table 2). The results of the coefficient of variation are much lower than 20%, which is within the uncertainty of the test method.

The following heat and smoke release parameters were measured for the tested cables: peakHRR_{av}, THR_{1200s}, TSP_{1200s}, and peakSPR_{av}. The test results were analyzed regarding five aspects according to Figure 1. The discussion is presented below except for the third aspect (no conductors), which was the subject of an earlier publication [1].

4.1. Material Used for the Conductor Construction

Specimens Nos 1, 2, 3, and 4 (Table 1) were non-halogenated cables and differed only in the material used for the conductor construction.

In the case of specimen Nos 3 and 4 with aluminum conductors, lower values of heat parameters were obtained than for cables with copper conductors (Nos 1 and 2 in Figure 5), which was up to four times lower in the case of the peakHRR_{av} result for specimen No 2 in relation to the peakHRR_{av} result for specimen No 4. The thermal conductivity of solid copper is equal to 401 W/(m × K), whereas for pure aluminum it is equal to 237 W/(m × K) [24]. Therefore, aluminum wires accumulate heat and its transfer is slower than for copper wires, causing lower values of the peakHRR_{av} and THR_{1200s} parameters for specimen Nos 1 and 2. The values of the heat of combustion for aluminum (in the form of powder) is equal to 31 MJ/kg (7.43 kcal/g) [25,26] and for copper it is equal to 2.4 MJ/kg (156 kJ/mole) [27] (almost 13 times lower than for aluminum). Moreover, aluminum can be involved in the combustion process to a certain degree. Smoke parameters do not differ significantly because the non-metallic volume of cables and the chemical nature of the materials used are similar in each case. To the best of the authors’ knowledge, this aspect has not been reported in the literature data before.
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The test results for specimen Nos 3 and 4 show lower heat release and smoke production values than for the corresponding specimen Nos 1 and 2, mainly due to the lower non-metallic volume of the combustible material of those cables.

4.2. Conductor Cross-Section Shape

Cable specimen Nos 12, 13, 14, and 15 were designed for the same low voltage rating (0.6/1 kV). Specimen Nos 12 and 14 and specimen Nos 13 and 15 had the same number of conductors and cross-sectional area (Table 1).

The test results were similar in each case and were relatively low. The non-dependency of the fire properties of cables with sector-shaped and round cross-section-shaped conductors was demonstrated in the case of specimen Nos 12 and 14 (Figure 6), which are similar in construction except for the cross-section shape of the conductor.

Cable parameters χ (1) for cable No 12 (equal to 4.0) and cable No 14 (equal to 4.5) are similar and relatively low, which causes the similarities in the results.

For specimen Nos 13 and 15, however, the difference in heat and smoke parameters is significant. Higher values were obtained for the cable with round copper conductors than the cable with sector-shaped copper conductors, almost six times higher in the case of peakHRRav, two times higher in the case of THR1200s parameter, and almost three times higher in the case of both smoke production parameters. This was expected because of the close packaging of metallic conductors, which creates a barrier for flame penetration inside the closed agglomeration of metallic wires, and a difference in cable parameter χ, which is lower for the cable containing the sector-shaped conductor.

To the best of the authors’ knowledge, no literature data exists on the influence of the conductor shape on the fire properties of electric cables.
Figure 5. Heat release and smoke production results for cables with different conductor construction.

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4.3. Number of Conductors

Non-halogenated cables with different numbers of conductors in their construction have previously been examined [1]. It was found that the construction of the cable influences its fire behavior. The barrier for flame penetration through the closed agglomeration of metallic conductors, the occurrence of intumescent structures formed from ATH/ZnB fillers, and the effect of its fire retardants during self-sustained combustion create better fire properties than those observed for single-conductor cables [1].

4.4. Materials Used for the Formulation of Non-Metallic Elements

The maximum values of peakHRR\(_{av}\) and THR\(_{1200s}\) were obtained for specimen Nos 5 and 6 (Figure 7), whereas for specimen Nos 7 and 8, the results were relatively low. The highest level for each parameter was obtained for cable No 6 (peakHRR\(_{av}\) = 229 kW, THR\(_{1200s}\) = 67 MJ, TSP\(_{1200s}\) = 155 m\(^2\), and peak SPR\(_{av}\) = 0.48 m\(^2\)/s), consisting only of a PVC-based outer sheath and insulations and non-vulcanized rubber (EPDM) as a bedding. Both cables burned completely, and only conductors and inorganic fillers were left behind on the test ladder.
which the stable intumescent structure is formed from ATH process and the formation of a glassy layer on the material’s surface [1,16,32].

Water as a product of chemical reaction (2) eliminates air from the combustion zone and dilutes the flammable gases:

\[
2\text{Al(OH)}_3 \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O.} \quad (2)
\]

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of ZnB and ATH consists of an endothermic release of water during the thermal decomposition non-halogenatedPVC

The higher TSP_{1200s} and peakSPR_{av} values obtained for cable specimen Nos 5 and 6 can be explained as follows: In poly(vinyl chloride) (PVC)-containing cables, a large amount of volatile saturated, unsaturated, and aromatic hydrocarbons, as well as char, was formed during combustion processes, mostly through cyclisation and chain scission radical reactions (Figure 8) [28,29].

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Figure 7. Heat release and smoke production results for cables of different non-metallic construction materials.

The heat release rate is proportional to oxygen consumption during the combustion process for most combustible materials and is assessed indirectly by using the concentrations of products of complete combustion [30]. Thus, the high concentrations of CO₂, CO, and hydrocarbons generated during the combustion process preceded by oxidizing reactions of PVC materials may be the result of the typical radicals reaction for poly(vinyl chloride) (PVC)-containing cables [31]. This resulted in the higher heat and smoke parameters obtained for halogenated cables.

The heat and smoke parameters of specimen Nos 5 and 6 were much higher than those for specimens of a similar construction (Nos 7 and 8). The low values of fire parameters were obtained for cable No 8 (peakHRR_{av} = 21 kW, THR_{1200s} = 13 MJ, TSP_{1200s} = 32 m², and peakSPR_{av} = 0.05 m²/s) for which the stable intumescent structure is formed from ATH/ZnB fillers, (2) reducing flammability within the cable’s outer sheath during a self-sustained combustion process. The cooperative flame-retardant effect of ZnB and ATH consists of an endothermic release of water during the thermal decomposition process and the formation of a glassy layer on the material’s surface [1,16,32]. Water as a product of chemical reaction (2) eliminates air from the combustion zone and dilutes the flammable gases:

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A number of research works have been done on the influence of poly (vinyl chloride) on the fire properties of materials so far, i.e., [5,6,11,14,23,33]. However, cables that vary in more than one constructional parameter were taken for those investigations and those results are not comparable with those of the authors’ recent study. On the other hand, the superiority of halogen-free flame-retarded materials over PVC-based materials used as cable sheaths and insulations on fire properties of electric cables is confirmed.

4.5. Concentric Barrier

For cables that consist of galvanized steel armor or copper concentric conductors (wires and tape) placed between the outer sheath and bedding (specimen Nos 10 and 11), much lower heat parameters, such as peakHRR_{av} and THR_{1200s}, parameters, were observed than for similar cables without any armor (specimen Nos 8 and 9) (Figure 9). In general, the measured values are relatively low. However, higher values of heat and smoke release parameters for specimen Nos 8 and 10 were obtained (as shown in the table below the chart). This is due to the nature of the material used for the outer sheath formulation.

![Heat release and smoke production results for cables with or without armor and concentric conductor.](image)

The EN 50399 test conditions [20] force the flaming (real scale) propagative processes and more CO_{2} as a product of complete combustion is produced, which results in higher heat release properties of cables in the case of specimen No 9. This phenomenon may be additionally reinforced by the flame-retardant process during thermal treatment of EVA filled with ATH and ZnB compounds. The additional water is formed during the flame-retardant process, which causes self-ignition.

The highest amount of smoke characterized by the TSP_{1200s} parameter (equal to 32 m^{2} for cable specimen No 8) resulted from the extent of damage within the test specimen expressed by the flame spread parameter and was equal to 1.12 m. For cable specimen No 9, the flame spread of 1.32 m gave a similar tendency as for specimen No 8. The damages covered pieces of the cables over their diameter and the flame penetrated the inner construction elements of the cables, which then self-extinguished. The area of burned polymeric material decreased the amount of fire effluents as a product of the complete and incomplete combustion process.
It was assumed that the metallic armor forms a natural barrier against flame penetration inside the cable, protecting it from internal flame propagation towards its inner bedding and conductors’ insulation. This phenomenon causes lower heat and smoke parameters for the cables.

The cables with and without armor were also tested within the FIPEC project [23] and CEMAC project [11] and the influence on the fire properties has been mentioned by Grayson et al. [19]. However, it is not possible to compare the results with the current investigation, because the other constructional-material parameters of cables were changed in the previous study, so a direct comparison is not possible.

5. Conclusions

Certain constructional-material parameters of electric cables positively influence the mechanical and electrical properties of cables but at the same time contribute to the deterioration of their fire properties.

1. The construction, number of conductors, and presence of armor or concentric metallic conductors improves fire properties by forming a barrier against flame penetration in the cable.
2. The use of copper conductors resulted in a decrease of the fire parameters studied in comparison with cables including aluminum conductors (peakHRRav parameter was even four times lower for the copper cable)
3. Construction materials based on non-plasticized poly(vinyl chloride) (PVC) significantly reduce fire properties of cables than halogen-free materials (LS0H), such as silane cross-linked polyolefin (XLPO), ethylene-acrylic copolymers (EVA), non-vulcanized rubber (EPDM), polyethylene (PE), and cross-linked polyethylene (XLPE) (peakHRRav parameter more than 17 times higher for the fully halogenated cable), which is due to the decomposition process of PVC material.
4. There is no clear relationship shown between the fire parameters and the cable parameter, $\chi$.

The results of this work would be useful and interesting for the wider research community interested in this subject as well as producers, engineers, designers, architects, independent consultants, approving authorities, and policy makers.

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References

1. Kaczorek-Chrobak, K.; Fangrat, J. Relationship between Non-Metallic Material Content and Fire Properties of Electric Cables. *Fire Mater.*. under review.
2. Kaczorek-Chrobak, K.; Fangrat, J.; Papis, B.K. Instalacje Elektryczne a Bezpiecze´stwo Po ˙ zarowe Budynków (Evaluation of Electrical Installations in terms of Fire Safety of Buildings). In Proceedings of the 65th Scientific Conference, Krynica-Zdrój, Poland, 15–20 September 2019. (In Polish).
3. Huang, X.; Nakamura, Y. A Review of Fundamental Combustion Phenomena in Wire Fires. *Fire Technol.* 2019, 1–46. [CrossRef]
4. Lenartowicz, R.; Fangrat, J. Electrical installations supplying fire safety equipment. In *Instalacje zasilaj ˛ ace Urz ˛ adzenia Bezpiecze´ stwa Po ˙ zarowego*; Monografia ITB: Warszawa, Poland, 2016; Volume 1. (In Polish)
5. Delichatsios, M.A.; Delichatsios, M.M. Upward Flame Spread and Critical Conditions for PE/PVC Cables in a Tray Configuration. In Proceedings of the Fourth International Symposium on Fire Safety Science, Ottawa, ON, Canada, 13–17 July 1994; pp. 433–444.
6. Fernandez-Pello, A.C.; Hasegawa, H.K.; Staggs, K.; Lipska-Quinn, A.E.; Alvares, N.J. A Study of the Fire Performance of Electrical Cables. In Proceedings of the Third International Symposium on Fire Safety Science, Bristol, UK, 13–15 February 2007; pp. 237–247.
7. Yanga, H.; Fua, Q.; Chenga, X.; Yuenc, R.K.K.; Zhanga, H. Investigation of the flammability of different cables using pyrolysis combustion flow calorimeter. *Procedia Eng.* 2013, 62, 778–785. [CrossRef]

8. Carcillo, M.; Caro, A.-S.; Sonnier, R.; Ferry, L.; Gesta, E.; Lagreve, C. Fire behaviour of electrical cables in cone calorimeter: Influence of cables structure and layout. *Fire Saf. J.* 2018, 99, 12–21.

9. Braun, E.; Shields, J.R.; Harris, R.H.F. Fammability Characteristics of Electrical Cables Using the Cone Calorimeter; NIST Report NISTIR 88 4003; National Institute of Standards and Technology, Center for Fire Research: Gaithersburg, MD, USA, 1989.

10. Hirshler, M.M. Survey of fire testing of electrical cables. *Fire Mater.* 1992, 16, 107–118. [CrossRef]

11. Journeaux, T.; Sundström, B.; Johansson, P.; Försth, M.; Grayson, S.; Gregory, S.; Messa, S.; Lehrer, R.; Kobilsek, M. CEMAC—CE-Marking of Cables; SP Rapport NV-2010:27; SP Technical Research Institute of Sweden: Borås, Sweden, 2010.

12. Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. *Off. J. Eur. Union* 2011, L88, 5–43.

13. Wiatr, J.; Lenartowicz, R.; Orzechowski, M. *Podstawy Projektowania i Budowy Elektroenergetycznych Linii Kablowych SN*. Zeszyty dla Elektryków; Dom Wydawniczy Medium: Warszawa, Poland, 2009.

14. Kaczorek-Chrobak, K. Reakcja na ogień kabli bezhalogenowych oraz kabli na bazie PVC (Reaction to fire of PVC based halogen-free electric cables). *Elektroinfo* 2015, 10, 25–27. (In Polish)

15. Kaczorek-Chrobak, K. Toksyczne produkty spalania izolacji i powłok kabli elektroenergetycznych (Toxic combustion products of insulations and outer sheaths of cables). *Elektroinfo* 2015, 5, 24–27. (In Polish)

16. Kaczorek, K. Bench-Scale Fire Toxicity Measurements of Polymers and Cables. Master’s Thesis, University of Central Lancashire, Preston, UK, February 2009.

17. Kaczorek-Chrobak, K.; Kolbrecki, A. Reakcja na ogień kabli elektroenergetycznych (Reaction to Fire of Electric Cables). *Materiały Budowlane* 2015, 7, 40–43. (In Polish)

18. CLC/TS 50576:2016 Electric Cables—Extended Application of Test Results for Reaction to Fire; CEN/CENELEC: Brussels, Belgium, 2017.

19. Sundström, B.; Försth, M.; Johansson, P.; Grayson, S.; Journeaux, T. Prediction of Fire Classification of Cables. Extended Application of Test Data. In *Extended Application of Test Data*. In Proceedings of the 12th International Fire Science & Engineering Conference Interflam, Nottingham, UK, 5–7 July 2010.

20. EN 50399:2011 +A1:2016 Common test methods for cables under fire conditions—Heat release and smoke production measurement on cables during flame spread test—Test apparatus, procedures, results. bs 2011. [CrossRef]

21. Grayson, S.J.; Van Hees, P.; Green, A.M.; Vercellotti, U. Assessing the Fire Performance of Electric Cables (FIPEC). *Fire Mater.* 2001, 25, 49–60. [CrossRef]

22. Foesth, M.; Sjostrom, J.; Wickstrom, U.; Andersson, P.; Girardin, B. Characterization of the thermal exposure in the EN 50399 cable test apparatus. In Proceedings of the 14th International Conference and Exhibition on Fire and Materials 2015, San Francisco, CA, USA, 2–4 February 2015; pp. 23–37.

23. Grayson, S.J.; Van Hees, P.; Vercellotti, U.; Breulet, H.; Green, A.M. *Fire Performance of Electric Cables—New Test Methods and Measurement Techniques (FIPEC)*; Final Report of European Commission; Interscience Communications Ltd: Hampshire, UK, 2010.

24. Lide, D.R. *CRC Handbook of Chemistry and Physics*, 85th ed.; CRC Press: Boca Raton, FL, USA, 2004.

25. Holley, C.E., Jr.; Huber, E.J., Jr. *The Heat of Combustion of Magnesium and Aluminum*; Los Alamos Scientific Laboratory: New Mexico, NW, USA, 1951.

26. Gupta, B.L.; Varma, M. Ignition and combustion studies on metallized UDMH-RFNA bipropellant system. *Indian J. Eng. Mater. Sci.* 1999, 6, 13–21.

27. Abbud-Madrid, A.; Fiechtner, G.J.; Branch, M.C.; Daily, J.W. Ignition and Combustion Characteristics of Pure Bulk Metals: Normal-Gravity Test Results. In Proceedings of the 32nd Aerospace Sciences Meeting & Exhibit, Reno, NV, USA, 10–13 January 1994.

28. Kaczorek-Chrobak, K.; Fangrat, J. Combustion Products Dependence on Ventilation Conditions for PVC-Insulated Electric Wire. In Proceedings of the 11th Mediterranean Combustion Symposium, Adeje, Spain, 16–20 June 2019.

29. Cullis, C.F.; Hirschler, M.M. *The Combustion of Organic Polymers*; Oxford University Press: New York, NY, USA, 1982.
30. Babrauskas, V. Heat Release Rates. In SFPE Handbook of Fire Protection Engineering, 5th ed.; Hurley, M.J., Gottuk, D.T., Hall, J.R., Jr., Harada, K., Kuligowski, E.D., Puchovsky, M., Torero, J.L., Watts, J.M., Jr., Wieczorek, C.J., Eds.; Springer: Berlin, Germany, 2016.

31. Kaczorek-Chrobak, K.; Fangrat, J. Fire Effluent Toxicity of PVC-Insulated Electric Wire in Ventilation-Controlled Fires. *J. Hazard. Mater.* submitted.

32. McCarthy, S. Environmentally Benign Resins and Additives, for Use in the Wire and Cable Industry; Technical Report; The Massachusetts Toxics Use Reduction Institute, University of Massachusetts Lowell: Lowell, MA, USA, 2003; Available online: https://www.turi.org/TURI_Publications/Toxics_Use_Reduction_for_Industrial_Sectors/Wire_Cable/Environmentally_Benign_Resins_and_Additives_for_Use_in_the_Wire_and_Cable_Industry (accessed on 1 October 2019).

33. Barnes, M.A.; Briggs, P.J.; Hirschler, M.M.; Matheson, A.F.; O’Neill, T.J. 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 Mater.* 1996, 20, 1–16. [CrossRef]