

Calorimetric Behaviour of Electric Cables

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Abstract: A routine cone calorimeter procedure, the theoretical analysis method, based on a set of ignitability data from the cone calorimeter, has been performed. The five sets of ignition times at different irradiance levels were used for obtaining experimental data needed for analysis. The cone calorimeter tests were performed with horizontal specimens of the size 100 mm × 100 mm consisting of eight pieces of commercial poly(vinyl chloride) coaxial power cable. Specimen combustion was carried out under external heat flux of constant values equal to 10, 20, 30, 40 and 50 kW·m⁻², respectively. Standard fire parameters and time to ignition were used for analysis. The results indicate that for each fire parameter, a rising trend with an increase in radiant heat flux has been observed. It was shown that the use of poly(vinyl chloride)-based cables is a potential fire safety hazard due to the emission of heat and a large amount of acid smoke. Quintiere's theory has been shown as a useful tool for fire modelling by using the data from small-scale tests rather than large geometrical scale cable experiments. Large scale cable test (EN 50399) results are also presented and compared with cone calorimeter data.

Keywords: fire properties of electric cables; Quintiere's theory; cone calorimeter tests of cables; large scale cable tests



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1. Introduction

There have been many cable tests performed using the cone calorimeter during the last three decades. Cone calorimeter is a powerful tool for the determination of parameters characterising fire properties of building products, particularly those involving the heat release rate. Moreover, experimental methods to obtain data for fire modelling are still being sought. Numerous examples have been published so far [1–4].

The thermodynamic properties of liquid materials, such as heat of combustion (EHC), heat of gasification, and burning rate per unit area, have been well measurable and are physically true, which is not reflected in the case of solid materials, especially when they are charring materials or include non-combustible fillers rather than melting [5] (forming a liquid phase) and evaporating.

Quintiere's theory derived from the observation that “many materials will not burn in the air without the addition of a radiant heat flux” [5] and is based on the splitting of solid materials into two groups: thermally thin and thermally thick. Thermally thin objects have no spatial, internal temperature gradient. Their thickness (d) is less than the thermal penetration depth. The simple theory of thermally thin ignition applies to materials of a thickness d , insulated on one side, or material of thickness $2d$, heated symmetrically. Examples of a thermally thin solid are a single sheet of paper, fabrics, and plastic films [6].

Thermally thick solids are more complicated, because the ignition of a solid might be approximated by a semi-infinite medium. Backface boundary conditions might be negligible in that case. The theory says that the time of ignition is always directly proportional

to incident radiant heat flux [6]. The thermally thick material always has a temperature distribution that is not influenced by the backface effect [5].

$$t_{ig} = \frac{\pi}{4} k \rho c_p \left(\frac{T_{ig} - T_0}{\dot{q}_e} \right)^2 \quad (1)$$

where t_{ig} is the time to ignition, s; k is the thermal conductivity, $W \cdot (m \cdot K)^{-1}$; ρ is the density of the material, $kg \cdot m^{-3}$; c_p is the heat capacity, $kJ \cdot (kg \cdot K)^{-1}$; $k\rho c_p$ is the thermal inertia factor; T_{ig} is the ignition temperature (or temperature to ignition); T_0 is the ambient temperature; and \dot{q}_e is the external incident heat flux at the surface.

A simplified analysis, similar to that developed by Quintiere, became the basis of the research of cables as thermally thick solids conducted by Fernandez-Pello et al. [7]. The predicted fire parameters were compared with experimental results, and it was shown that for most polymers, especially at high irradiance levels, the thermal degradation temperature may be used for ignition delay times. The key parameters responsible for the fire properties of cables have been indicated.

2. Basics of Quintiere's Theory

Besides the routine cone calorimeter procedure, a theoretical analysis method [8], based on a set of ignitability data from the cone calorimeter was performed. The five sets of ignition times (t_i) at different irradiance levels (q_c) were used for obtaining experimental data needed for analysis. The least-squares method was used with these data. The following equations, based on the work in ref [9], are used to obtain T_i and kpc , assuming that:

$$q_c = Y \quad (2)$$

$$X = \frac{1}{\sqrt{t_i}} \quad (3)$$

$$C_1 = \frac{\sqrt{\pi k \rho c}}{2} (T_i - T_0) \quad (4)$$

$$C_2 = 0.64 \varepsilon \sigma (T_i^4 - T_0^4) \quad (5)$$

$$Y = C_1 X + C_2 \quad (6)$$

where q_c is the external heat flux, $kW \cdot m^{-2}$; q_{cr} is the critical heat flux for ignition, $kW \cdot m^{-2}$; k is the thermal conductivity, $W \cdot (m \cdot K)^{-1}$; ρ is the density, $kg \cdot m^{-3}$; c is the heat capacity, $kJ \cdot (kg \cdot K)^{-1}$; T is the temperature, K; C_1 is the slope of the straight line plotted in an HRR graph; ε is the emissivity coefficient; and σ is the Stefan–Boltzmann constant, equal to $5.67 \times 10^{-8} W \cdot m^{-2} \cdot K^{-4}$.

Following the development by Quintiere [10–12] all of the properties in Table 1 can be useful inputs in fire computational fluid dynamics (CFD) modelling to predict fire growth with various modelling approaches. As explained in ref [5]: The word 'flammability' here is taken as a comprehensive measure of the fire growth capability for a material. As fire growth depends on the processes of ignition, flame spread, and energy release rate (HRR), it is these processes that constitute flammability. However, flammability is commonly judged concerning a given scenario, e.g., flammability of clothing, carpets, wall-linings, etc. Each of these scenarios has a different ignition mode and a different flame-generated heat flux that promotes the fire processes. Moreover, for each of the processes, there is a 'critical' heat flux below where ignition, flame spread, and burning will not occur.

Table 1. Summary of the studied flammability parameters of PVC cable, after Quintiere [10].

Parameter	Physical Meaning	Measurement Means
TRP Thermal Response Parameter (C_1 in Equation (2))	$\frac{\sqrt{\pi k \rho c}}{2} (T_i - T_0)$ For a given heat flux, TRP ² is directly proportional to the ignition time	Inverse slope of $t_{ig}^{-1/2}$ and applied heat flux
CHF Critical Heat Flux	Proportional to ignition temperature, and is the minimum heat flux needed for ignition	Proportional to ignition temperature, and is the minimum heat flux needed for ignition
HRP Heat Release Parameter	$\Delta h_c / L$ Heat of combustion/Heat of gasification	Slope of maximum heat release rate (peak HRR) and heat flux

3. Characteristic of Test Methods and Cable Samples

The typical widely used electric cables have been tested by means of large geometric-scale method described in the EN 50399 standard [13] supplemented by a cone calorimeter test method [1]. These experiments (Figures 1 and 2) have been performed on the commercial cables described in Table 2. Those cables are widely used in dwellings as a power and control cables.



Figure 1. External view of EN 50399 standard test chamber at the accredited ITB Fire Testing Laboratory in Pionki, Poland.

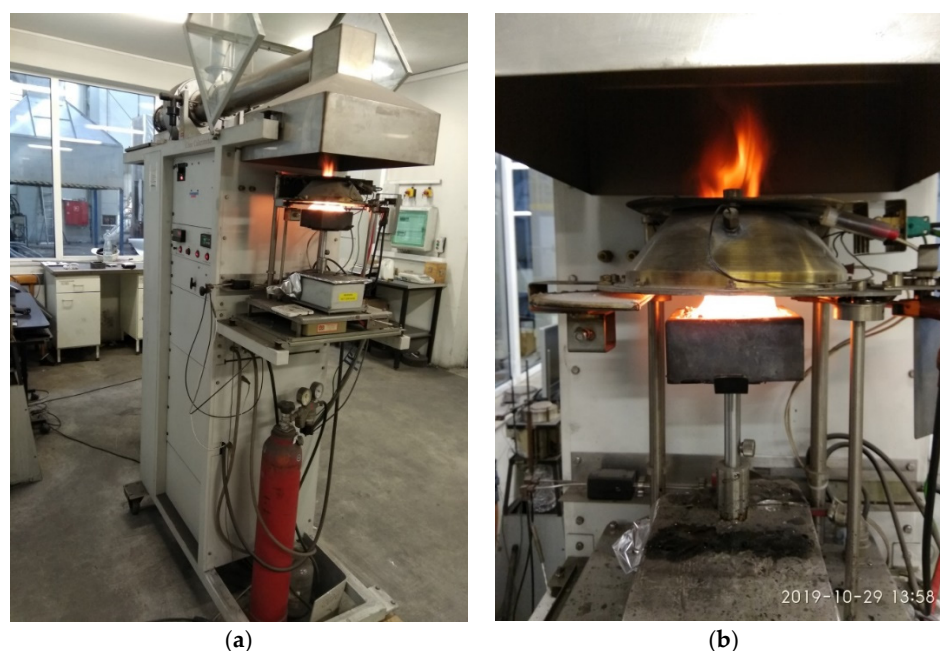


Figure 2. Cone calorimeter: (a) external view on the test apparatus, (b) cable specimen during the test, at the accredited Fire Testing Laboratory ITB in Pionki, Poland.

Table 2. Characteristics of cables tested by means of cone calorimeter and large geometric scale test methods.

Specimen No	Type of Cable	Cable Size	Cable Dimensions, mm ² or (mm × mm)	Weight of Cable, kg·km ⁻¹	Conductors	Insulations	Outer Sheath
1	optical fibre cable, non-halogenated	48 J	13.2	71	Optical fibre	LS0H compound	LS0H compound
2	coaxial power cable, non-halogenated	3 × 1 mm ²	5.1 × 9.6	82	Copper, round	XLPE	LS0H compound
3	copper control cable, non-halogenated	16 × 0.5 mm ²	11.1	192	Copper, round	LS0H compound	LS0H compound
4	coaxial power cable, halogenated	3 × 1.5 mm ²	3.8 × 8.5	76	Copper, round	PVC	PVC

Following the end-use application, a bunch of 19 pieces of PVC cable was tested inside the chamber in their end-use application. The 3.6 m long pieces of cables were mounted on a 4 m test ladder. A nominal burner HRR level of 20.5 kW, airflow rate through the chamber of $(8000 \pm 800) \text{ L}\cdot\text{min}^{-1}$, and a white light detector were used [13].

The cone calorimeter tests were conducted on each presented cable (Table 2) at the set radiant heat flux of $50 \text{ kW}\cdot\text{m}^{-2}$ to reflect real combustion conditions where rapid combustion is taking place. The cone calorimeter tests (Figure 2) were performed with horizontal specimens of the size of $100 \text{ mm} \times 100 \text{ mm}$. The surface of specimens was covered by the steel grid in order to minimize swelling of the cable during the test. The ends of the cable pieces were protected by aluminium foil to avoid additional inflammation.

Furthermore, specimens consisted of eight pieces of commercial PVC coaxial power cable (Specimen 4) (Figures 3 and 4, Table 3) tightly packed in the required stainless steel holder frame and with a ceramic wool fibre blanket of low density ($65 \text{ kg}\cdot\text{m}^{-3}$) as backing material according to the standard (Figure 3) were tested in five different set heat fluxes (Table 3).

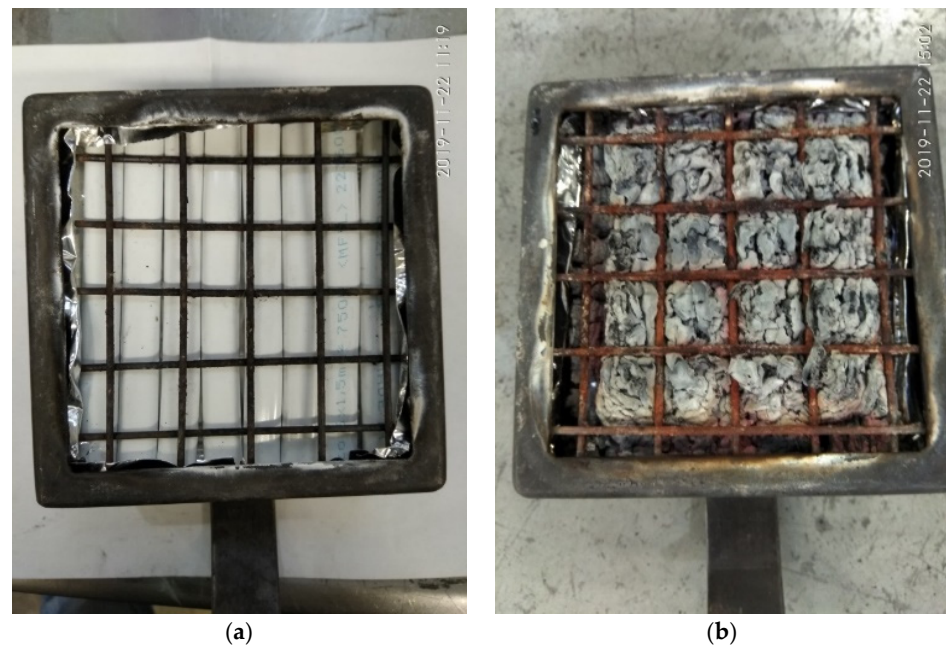


Figure 3. Cable specimen (100 mm × 100 mm) for cone calorimeter testing: (a) sample before the test, (b) sample after the test).

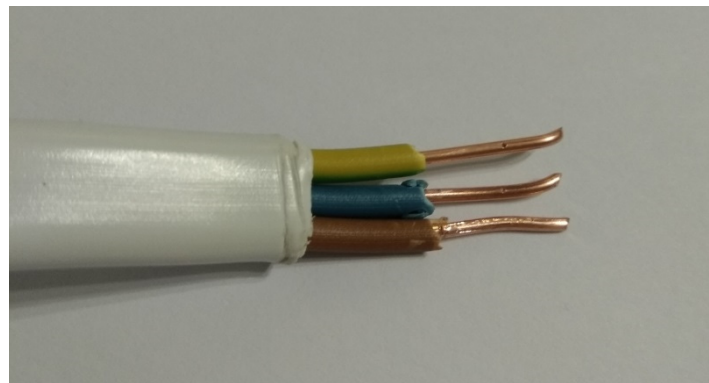


Figure 4. PVC-insulated and sheathed coaxial copper cable (cable specimen No. 4) typically used in electrical installation in buildings.

Table 3. Characteristics of cable specimen 4 and test conditions.

Specimen No	Cable Size	Cable Dimensions, mm × mm	Weight of Cable, kg·km ⁻¹	Conductors	Insulations	Outer Sheath	Heat Flux, kW·m ⁻²
1	3 × 1.5 mm ²	3.8 × 8.5	76	Copper, round	PVC	PVC	10
2							20
3							30
4							40
5							50

4. Cone Calorimeter Test Results and Discussion

Electric cables can be considered as composite materials, where the properties vary during the fire test. The fire properties of cables depend on the order of components which are burned. However, these kinds of materials of an unknown composition create

difficulties in determining the thermal inertia factor $k\rho c_p$, which characterises the thermal properties of materials responsible for the ignitability and flame spread [14].

During the test of the PVC coaxial power cable, the various parameters related to heat release, time to ignition and smoke production were obtained (Table 4).

Table 4. Cone calorimeter results for coaxial power PVC-based cable (specimen 4).

Specimen No.	Heat Flux, $\text{kW}\cdot\text{m}^{-2}$	t_{ig} , s	$t_{\text{ig}}^{-1/2}$, $\text{s}^{-1/2}$	peakHRR, $\text{kW}\cdot\text{m}^{-2}$	TSP, m^2	Δm , g
1	10	no ignition	n/a	3.94	0	0.35
2	20	226	0.07	132.89	24	46.30
3	30	80	0.11	138.7	27.3	47.29
4	40	46	0.15	169.78	32.1	46.44
5	50	41	0.16	176.84	34.3	46.57

A linear relationship between the maximum heat release rate (peakHRR) and external radiant heat flux has been obtained (Figure 5), as might be expected. The peakHRR increased together with the increasing set cone radiation. An HRP parameter has been obtained as a slope of the trend line of peakHRR dependence curve on radiant heat flux, and was equal to 3.8.

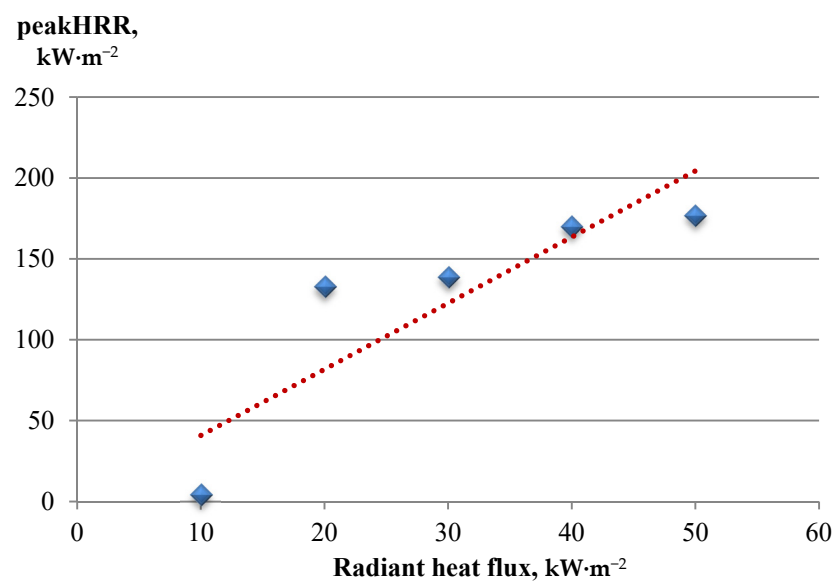


Figure 5. peakHRR as a function of radiant heat flux for a PVC coaxial power cable.

The total smoke production parameter (TSP) increased together with the increasing radiant heat flux (Figure 6). There was almost no smoke that occurred during pyrolysis combustion during the test involving $10 \text{ kW}\cdot\text{m}^{-2}$ radiant heat flux, and the cable sample was almost undamaged during the test. This is due to differences in the mass loss of the sample, which varied from $10 \text{ kW}\cdot\text{m}^{-2}$ (equal to 0.35 g) radiant heat flux up to 46.3–47.3 g for flaming combustion under 20–50 $\text{kW}\cdot\text{m}^{-2}$ radiant heat flux.

In the case of an external heat flux equal to $10 \text{ kW}\cdot\text{m}^{-2}$, the specimens were not ignited during the period of 1800 s from the beginning of the test. The fire effluents which were observed, and the total mass loss of 8% of the specimen, indicated the presence of a pyrolysis process. The linear relationship between time inverse $t_{\text{ig}}^{-1/2}$ and radiant heat flux for PVC coaxial power cable is shown in Figure 7.

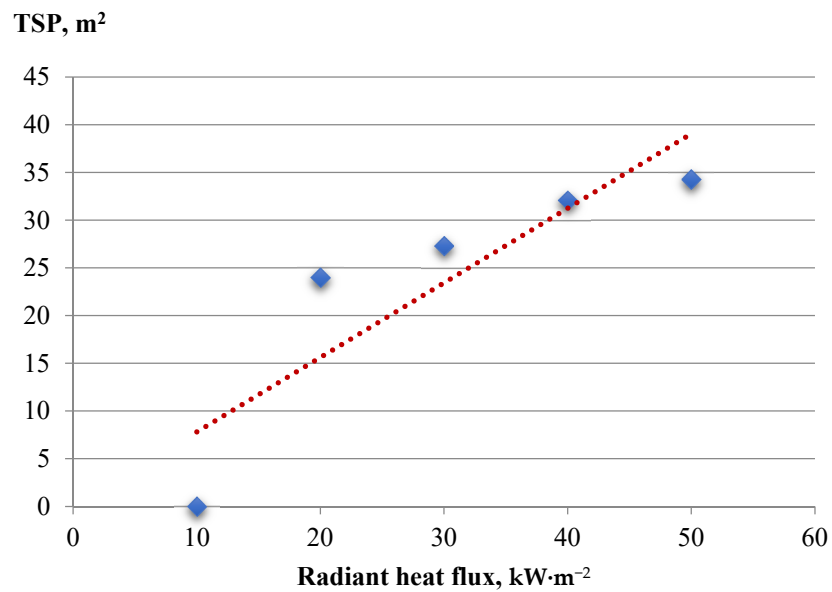


Figure 6. Total smoke production (TSP) as a function of radiant heat flux for a PVC coaxial power cable.

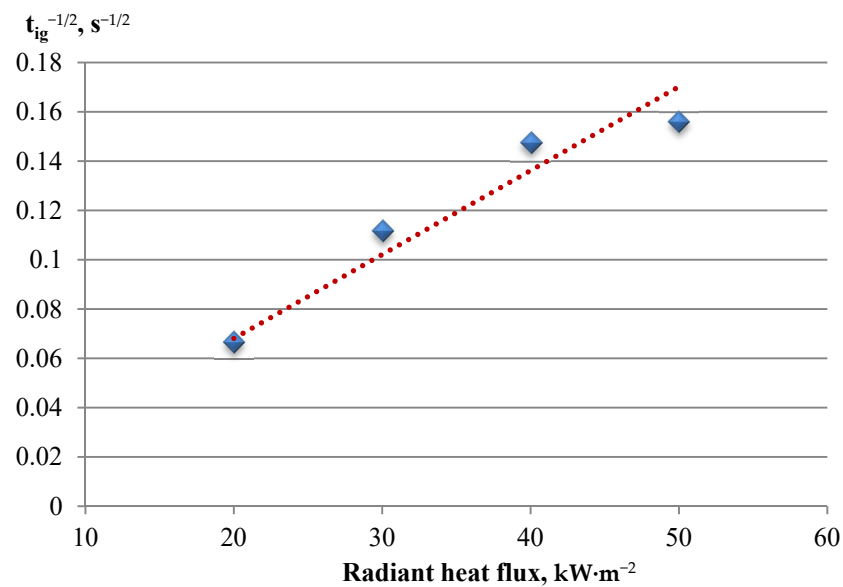


Figure 7. The relationship between time inverse and radiant heat flux for a PVC coaxial power cable.

The presented results (Figures 5 and 7) are very similar to those available in the literature for homogeneous solid materials, such as various wood samples and plastic foams [5,6,11,12,15], and also for electric cables [16], confirming that Quintiere's theory applies to the fire modelling of electric cables, provided that the coefficients characteristic values of a solid material involved are known.

The construction of the three-conductor electric cable (Figure 8) shows the presence of a relatively thin PVC outer sheath, which is a crucial element for piloted ignition and surface flame spread, it being the first material ignited. Therefore, it was assumed that the theory for thermally thin materials would also apply.

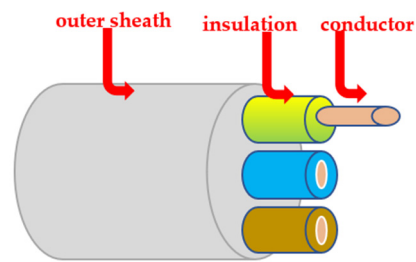


Figure 8. Schematic of a 3-conductor cable sample.

Using the analysis of measurements for thin materials [6], the data were plotted as the reciprocal time of piloted ignition (Table 1) versus radiant heat flux (Figure 9). The linear behaviour is clearly visible. One can calculate the critical heat flux as equal to $12 \text{ kW}\cdot\text{m}^{-2}$. This result is in line with the literature data reported for halogenated PVC [6]. In conclusion, the thermally thin material approach would also apply to more complex multi-layered products, e.g., electric cables.

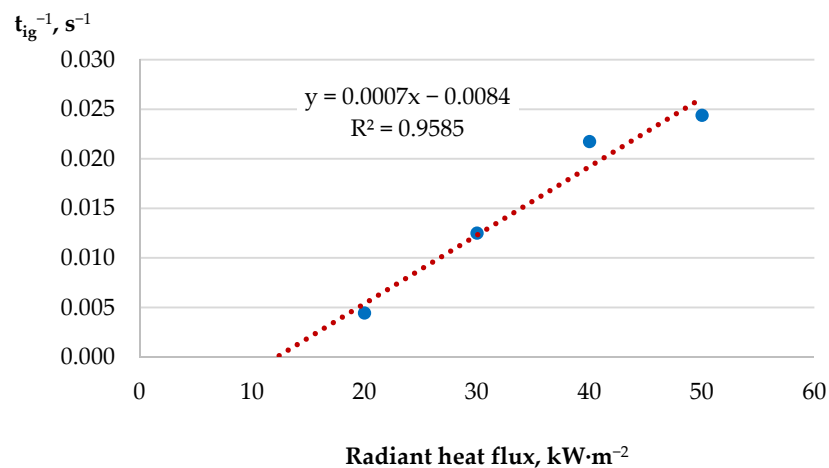


Figure 9. Reciprocal time results for piloted ignition of a PVC coaxial power cable.

Additionally, experimental results under the consideration of smoke release have been included. The rate of smoke release parameters during the test varied significantly, depending on the external set heat flux (Figure 10).

The highest peak of smoke release (equal to $14.89 \text{ (m}^2\cdot\text{s}^{-1})\cdot\text{m}^{-2}$) was obtained for the $50 \text{ kW}\cdot\text{m}^{-2}$ radiation, and the lowest for $10 \text{ kW}\cdot\text{m}^{-2}$ (equal to $0.45 \text{ (m}^2\cdot\text{s}^{-1})\cdot\text{m}^{-2}$) where no ignition occurred, and the value increased together with increasing heat flux. The time period of smoke release also depended on the radiant heat flux and finished with flameout of test specimens.

From the comparison of test results from the cone calorimeter with tests of a large geometric scale, Quintiere's theory supplemented with cone calorimeter data for cables might be useful to simplify the experiments on the fire safety of building products.

The most important observation after the large-scale cable test was that the whole cable specimen had been burned within the 1200 s test period (FS = 3.5 m) (Figure 11).

The values of other fire properties, such as peakHRR (related to oxygen consumption) and peakSPR, are presented as the maxima in Figure 12.

The obtained peakHRR (equal to $185 \pm 6.6 \text{ kW}$) and peakSPR (equal to $2.37 \pm 0.06 \text{ m}^2\cdot\text{s}^{-1}$) values are relatively high in the case of heat evolved during the combustion process. Those parameters increased rapidly and then declined, which indicates a significant influence of the cable on the fire development in the fire room.

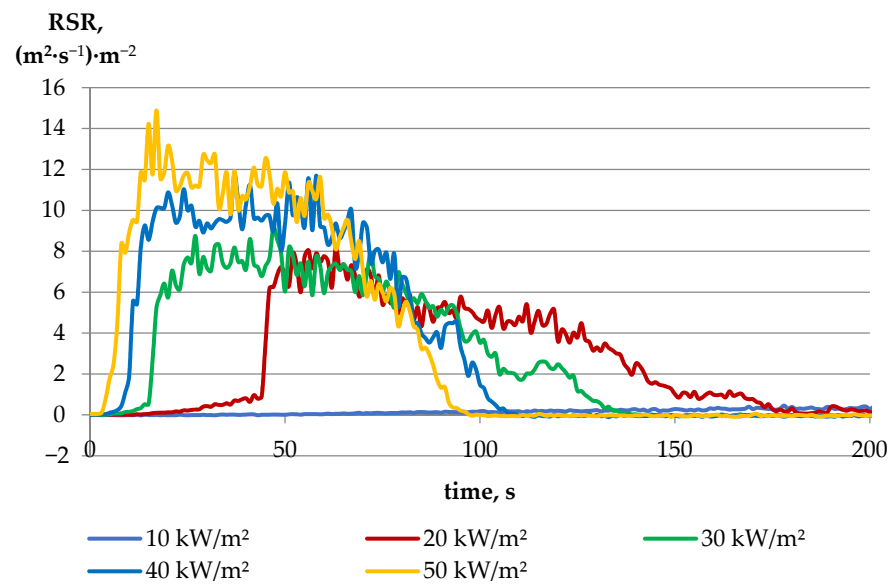


Figure 10. Rate of smoke release (RSR) as a function time for PVC coaxial power cable tested in cone calorimeter.

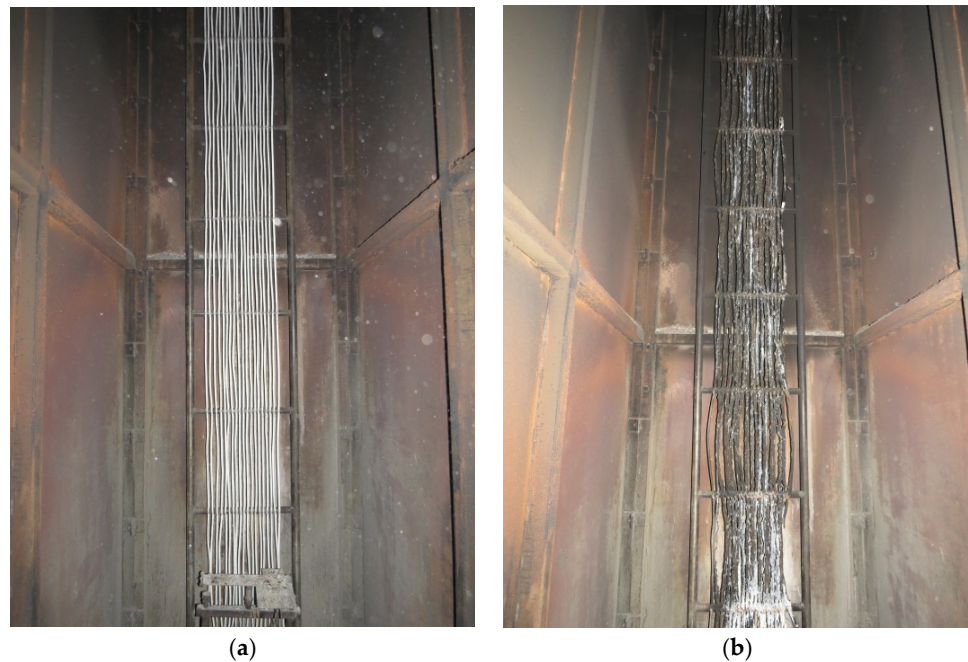


Figure 11. PVC-insulated and sheathed coaxial cable on the test ladder according to EN 50399 standard: (a) before the test, (b) after the test.

The cable was burned completely, and only char, the inorganic filler's residue, and copper wires, were left behind after the test (Figure 11). The maximum value of smoke production parameter (peakSPR equal to $2.37 \pm 0.06 \text{ m}^2 \cdot \text{s}^{-1}$) for the cable was also high, which was due to the decomposition reaction of poly(vinyl) chloride during the combustion process. A large amount of volatile saturated, unsaturated, and aromatic hydrocarbons, as well as char, was then formed during the combustion processes. Mostly, cyclisation and chain scission radical reactions are responsible for the production of visible smoke species [17–19]. The toxicity of cables is discussed in detail in another publication by the authors [20].

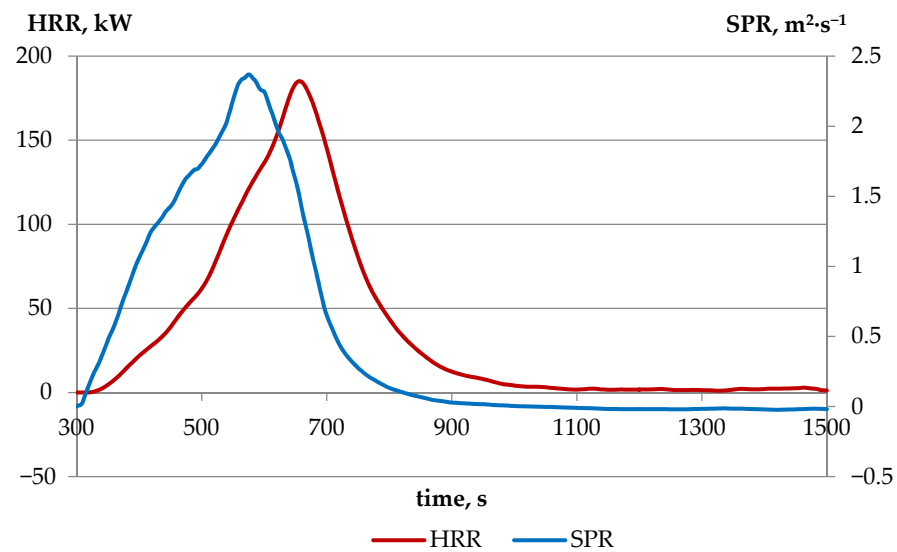


Figure 12. Heat release rate and smoke production rate results for a PVC-insulated and sheathed coaxial power cable.

The direct comparison of heat release data obtained in large scale test (EN 50399) and the cone calorimeter do not show good correlation. Nevertheless, using the concept of modified heat of combustion (MHC) [20,21], measurements made by two methods (EN 50399 and cone calorimeter) can be combined and presented to express the fire behaviour of cables with increased accuracy.

The MHC concept may apply, in the case of total heat release measurements and mass loss, e.g., in a cone calorimeter of cables, then:

$$\text{MTHR} = \text{peak THR} \times \text{MLR} \quad (7)$$

where MTHR is the modified total heat release, $\text{MJ} \cdot \text{kg}^{-1}$; THR is the total heat release rate measured in the cone calorimeter, $\text{MJ} \cdot \text{kg}^{-1}$; and MLR is the relative mass loss rate measured in the cone calorimeter.

The correlation of THR measured in the large-scale test and peak THR obtained in the cone calorimeter method at $50 \text{ kW} \cdot \text{m}^{-2}$ was studied for four presented cables (Table 5).

Table 5. Cone calorimeter and large-scale experiment results for four cable samples.

Specimen No.	Cone Calorimeter						Large-Scale				
	t_{ig} , s	peakHRR, $\text{kW} \cdot \text{m}^{-2}$	THR, $\text{MJ} \cdot \text{m}^{-2}$	TSP, m^2	TSR, $\text{m}^2 \cdot \text{m}^{-2}$	Δm	MTHR, $\text{MJ} \cdot \text{m}^{-2}$	peakHRR, kW	THR, MJ	TSP, m^2	Flame Spread (FS), m
1	60	159.41	139.7	7.3	825.8	0.53	73.9	163.95	75.17	35	3.50
2	66	169.38	94.7	12.6	1423.4	0.42	39.3	91.6	46.83	86	3.50
3	58	140.53	121	21.4	2419.8	0.33	40.5	20.76	6.78	13	0.64
4	21	145.79	93	34.5	3899.3	0.37	34.6	185.11	44.19	598	3.50

The modified total heat release (MTHR) results obtained during the cone calorimeter experiment has been compared with total heat release (THR) data from large-scale cable experiment for four cables, which differ in their construction (Table 2). The presented results (Figures 13 and 14b) show the excellent correlation between MTHR and THR results for three of the four tested cables—those cables which were burned completely during both cone calorimeter and large geometric scale tests.

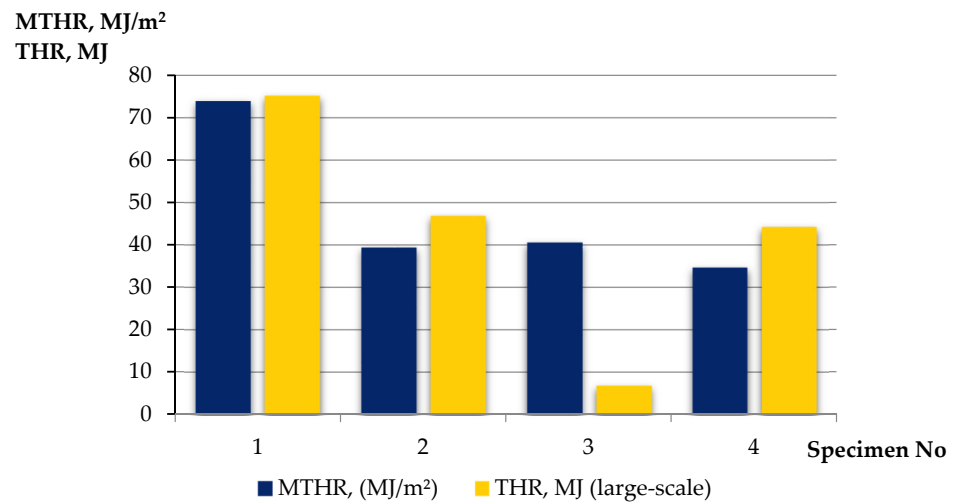


Figure 13. Comparison of MTHR and THR results for four tested cables.

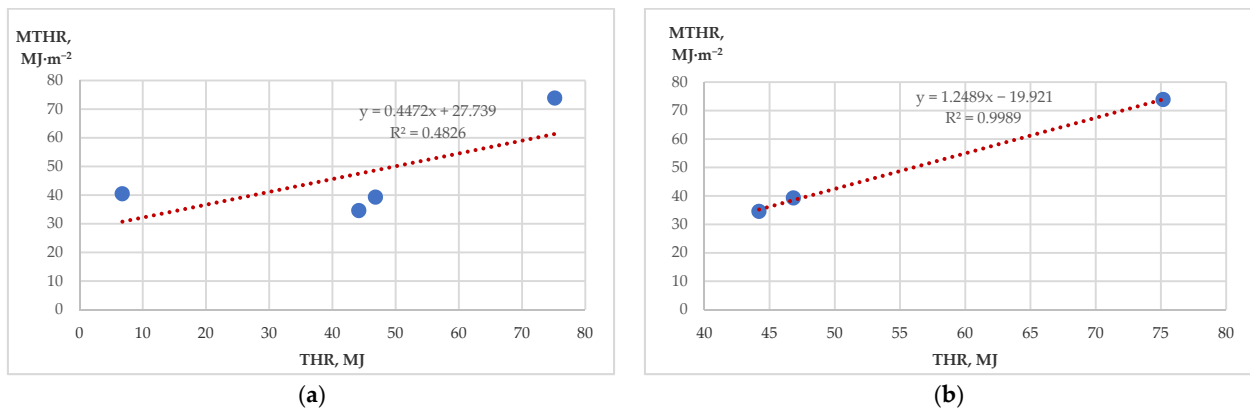


Figure 14. The linear correlations of MTHR and THR results for (a) specimens 1, 2, 3, 4, and (b) specimens 1, 2, 4.

Cable specimen No. 3 did not burn completely, and its flame spread (FS) was equal to 0.64 m. This phenomenon can be explained by the more complex construction of cable No. 3. Moreover, during the test on a cone calorimeter, differences in the heat release rate were noticed for all four cable samples (Figure 15), which resulted from differences in their structure.

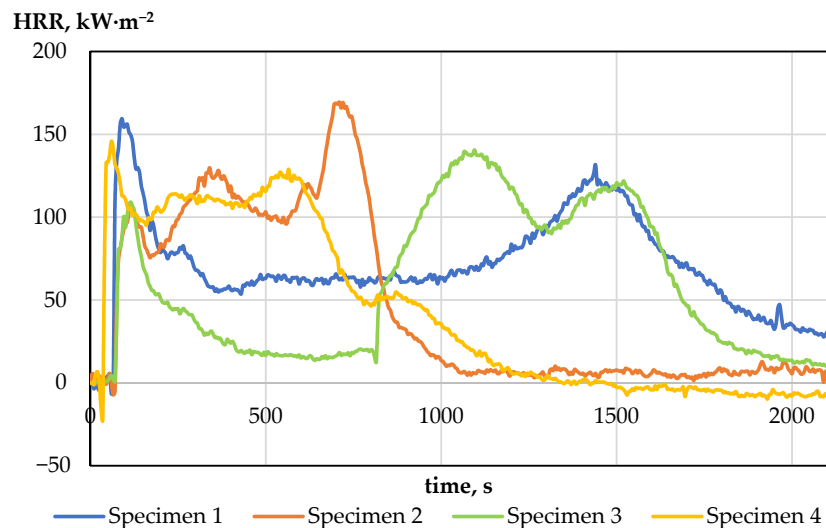


Figure 15. HRR as a function of time for tested cables on cone calorimeter.

5. Thermal Decomposition Processes on PVC Cable Combustible Elements (Supplement on the Analysis Performed)

Non-metallic materials (insulations and outer sheath) of the optical cable (cable specimen No. 1) burned and released heat relatively slowly and evenly over the entire test period, which was the result of the lack of metallic barriers or conductors inside the cable. Cable specimens No. 2 and 4 burned violently in the first minutes of the test, and after the fuel (non-metallic elements) was depleted, the combustion process declined at about 1000 s into the test. In the case of specimen No. 3, the outer sheath initially burnt. Then, the flame met a barrier in the form of a laminated aluminium foil screen, which resulted in the process of flaming combustion being quenched at 481 s into the test. After the barrier was damaged, the inside elements of the cable (filler and conductor insulations) rapidly reignited at about 895 s of test duration. However, this process was stretched over time due to the presence of 16 copper conductors creating a barrier to flame penetration inside the specimen. The dependencies of fire properties on construction and material parameters are explained in further details by the authors in a separately published article [14].

The thermal decomposition examination of a PVC-based coaxial power cable has been performed using the thermogravimetric analysis (TGA) analyser TA Instruments Q-500, in order to identify the thermal decomposition characteristics of the main combustible elements of cable specimen 4. The specimens of outer sheath and insulation were tested separately in platinum crucibles. The test was performed in the pyrolysis atmosphere of nitrogen, the $50 \text{ K}\cdot\text{min}^{-1}$ of decomposition speed was set.

Photos of the test specimens in the platinum crucibles before and after the thermal decomposition using the TGA method are shown in Figures 16 and 17. Figures 18 and 19 include the thermogravimetric analysis (TGA) decomposition curves for an outer sheath and insulation of tested a PVC coaxial cable, respectively. In the first phase of decomposition, hydrochloric acid (HCl) was evolved in the fire effluent in the temperature range $270\text{--}280 \text{ }^\circ\text{C}$ (Figures 16 and 17), which is shown as the first stage of a thermal decomposition and refers to the mass loss of the cable outer sheath equal to 55.9% and mass loss of cable insulation equal to 50.95%.

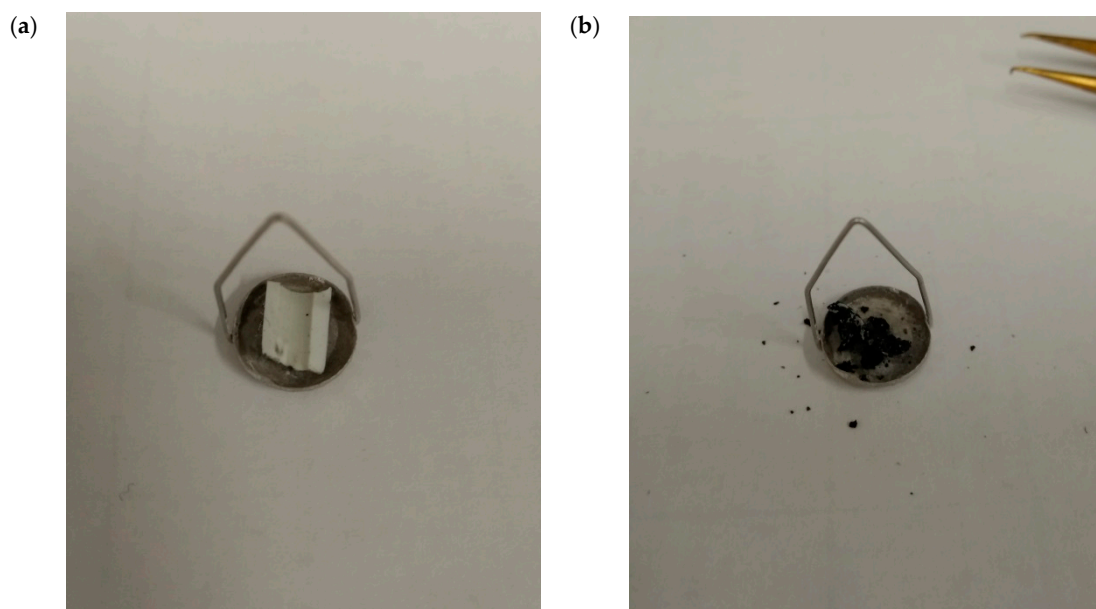


Figure 16. Outer sheath of a PVC coaxial cable placed in the TGA test platinum pan: (a) before the test, (b) after the test.

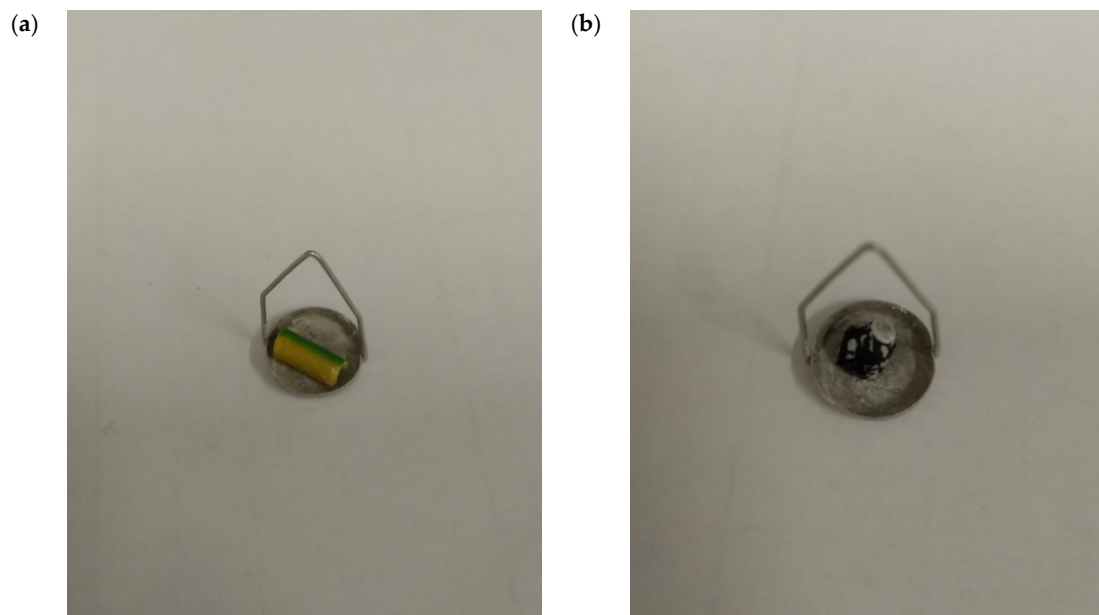


Figure 17. Insulation of a PVC coaxial cable placed in the TGA test platinum pan: (a) before the test, (b) after the test.

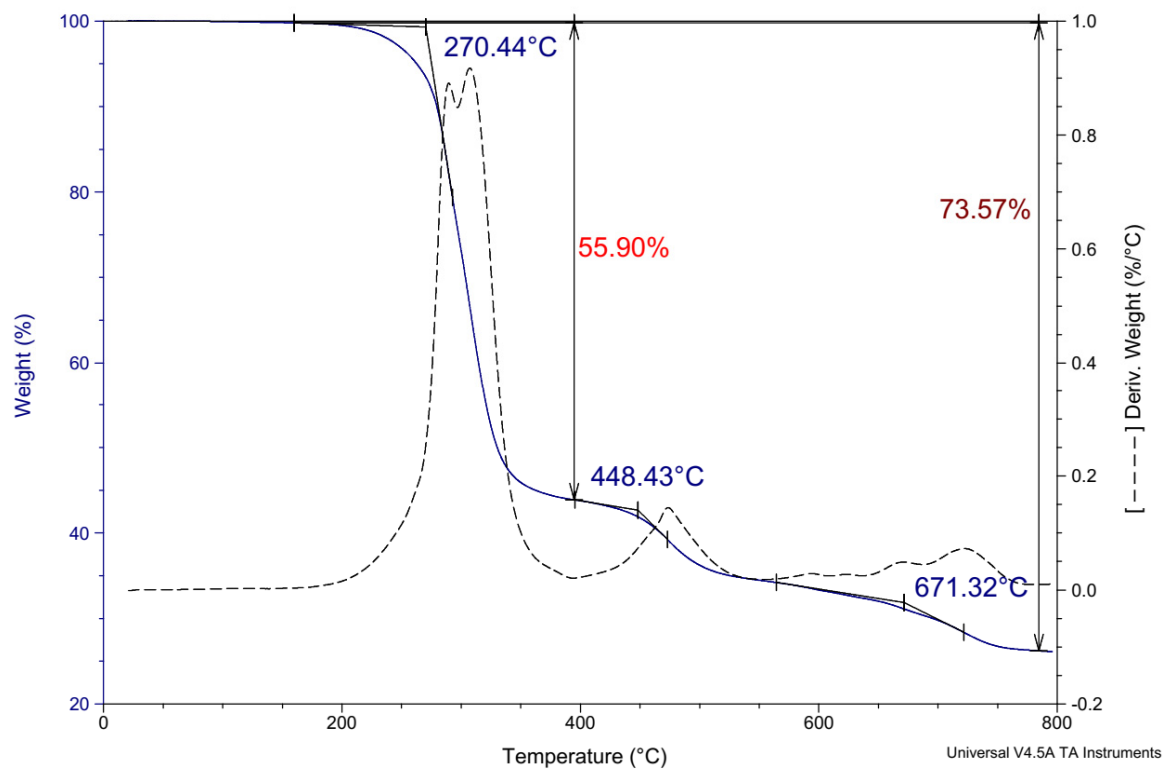


Figure 18. TGA decomposition curve for the outer sheath of a PVC coaxial power cable.

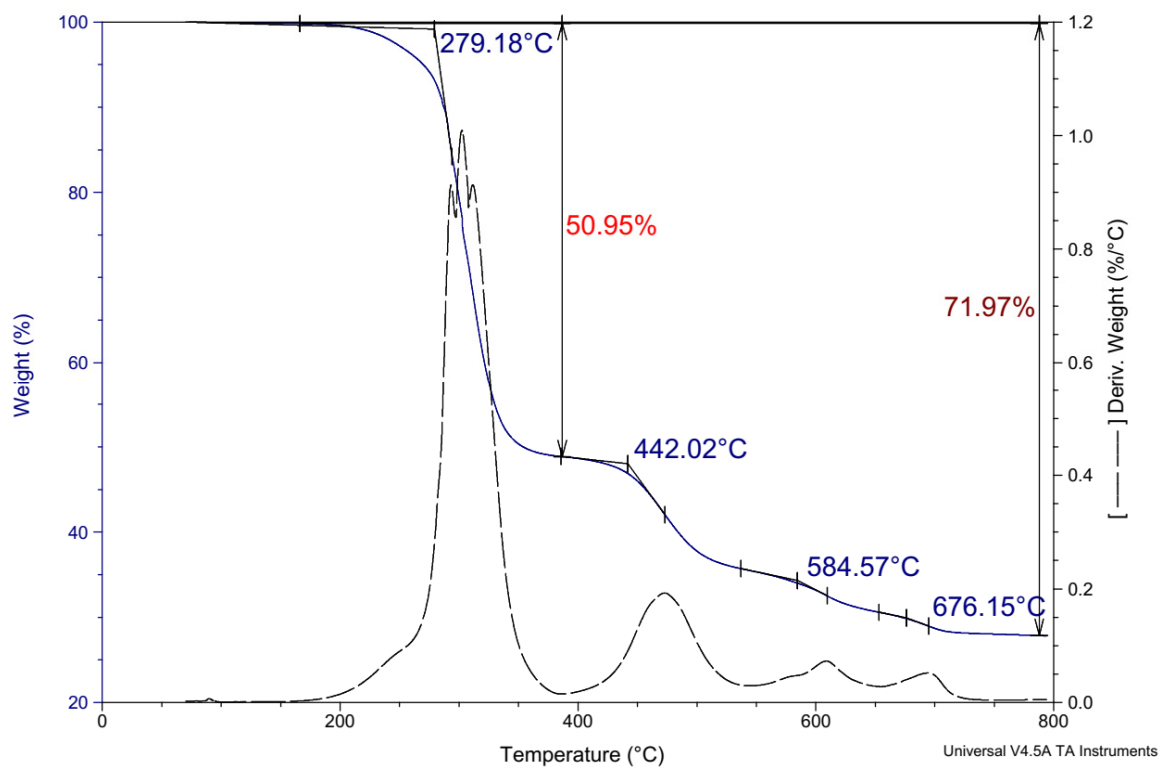


Figure 19. TGA decomposition curve for insulations of a PVC coaxial power cable.

The next stages of thermal decomposition of an outer sheath and insulation of a PVC cable were due to the polymer chain scission, where the combustible organic material was evolved as carbon content fire effluent species. Finally, the solid residue (char and inorganic filler) was left behind, amounting to about 20% of the initial mass of the cable constructional materials).

6. Summary and Conclusions

Heat release, the range of flame spread, and smoke generation parameters are significant factors increasing the fire properties of electric cables and, thus, the fire safety of entire buildings.

The following conclusions can be drawn from this study:

1. The analysis for cone calorimeter tests on electric cables based on Quintiere's theory proved that it is possible to replace large geometric scale fire tests with a simpler cone calorimeter method. Therefore, the obtained data from tests on a cone calorimeter can be used as input data for numerical modelling of cable fires, thus reducing the cost and time constraints of the real scale experiments.
2. An excellent correlation has been found between cone calorimeter test results (THR) modified by means of the experimental formula (MTHR) with semi-real scale experiment results (THR) for the cables burning completely.
3. The presented research has shown that the thermally thin material approach can also be applied to more complex multi-layered products, for instance, electric cables.
4. The obtained cone calorimeter results for PVC electric cable confirmed a strong relationship between fire properties and the incident radiant heat flux.
5. HCl particles are released in the first phase of combustion at temperatures as low as 270–280 °C, as indicated by the results of the thermogravimetric analysis. The use of PVC-based cables is a potential fire safety hazard due to the emission of heat and a large amount of acid smoke containing HCl particles, which irritating people's respiratory systems, obstruct the evacuation, and destroy electronic devices by corrosion processes.

Assuming that the application of Quintiere's theory to material fire tests can significantly reduce the number of tests, reducing their scale and optimizing them, it should be highlighted that this approach would allow the results to be expressed in terms of a limited number of parameters such as HRP, TRP and CHF [5]. It would not be possible to determine the fire parameters necessary for modelling for composite materials, e.g., cables, where individual values such as thermal conductivity, overall density and heat capacity are not known.

Simplifying the fire test protocol of cables should be considered further, as an application potential suggested in this article. The extended analysis will be performed for cables with a more complex construction and reported in the near future.

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