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CRITICAL HEAT FLUX DETERMINATION OF ELECTRIC CABLE INSULATION

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Abstract

Electric cables can contribute to the spread of fire through the insulating layer. This paper focuses on their properties characterizing the initiation of fire. Samples of ethylene-based cable insulation were tested using a cone calorimeter by exposing them to external heat flows of six different values (25 kW m^{-2} – 50 kW m^{-2}). Time to initiate flame burning was observed. The critical heat flux (depending on the method of calculation was in the range 2.94 kW m^{-2} – 4.59 kW m^{-2}) and the thermal response parameter (342 kW $s^{-0.5}$ m^{-2}) was calculated from the time of initiation and external heat flow dependence.

Key words

Cone calorimeter, time to ignition, critical heat flux, thermal response parameter

INTRODUCTION

Electrical cables are used extensively for both residential and industrial applications. They consist of conductors made of either copper or aluminium and insulation (or jackets) of synthetic polymeric materials. Several types of polymeric materials are used in cable constructions, varying in chemical structure, thickness, and additives. Depending on the applications, cables are either packed loosely or tightly, in horizontal, vertical or other orientations. (Tewarson, 1989) Electrical cables are complex assemblies including several polymeric parts (insulation, bedding, sheath) constituting fuel sources. Its fire behaviour is highly dependent on the heat flux. A dramatic transition occurs at a different heat flux according to the cable. (Meinier, et al., 2018) Ignition and burning of electrical cables are potential causes of fires in residential or industrial buildings. Moreover, cables may also lose their functions or be less efficient when exposed to heat sources (progressive change in resistance, deterioration of the signal quality, short-cut). (Courty, 2017)

Depending on their location and means of installation, cables can contribute to a fire in several ways. For example, burning cables can propagate flames from one area to another, can

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add to the fuel available for combustion and can liberate smoke and toxic and corrosive gases. The hazard from burning cables should be put in the context of the surroundings. Sometimes, cables form a very small proportion of the combustible material, while in other situations they can form the majority. (Moore, 2000.)

Halogen containing materials, as a group, tend to outperform non-halogen materials in terms of the major fire properties (Barnes et al., 1996):

- Heat release
- Ignitability
- Flammability

To produce materials formulated to meet the various insulation or jacketing performance requirements (e.g., heat and light stability, smoke retardancy, or water resistance), polymers and additives are combined together in a compounding operation. (Harriman, 2002.)

Additives represent a broad range of chemicals used by resin manufacturers, compounders, and fabricators to improve the properties, processing, and performance of polymers. From the earliest days of the plastics industry, additives have been used initially to aid these materials in processing and then to improve their properties. (Harper, 2000.)

Henrist et al. (2000) carried out interdiffusion experiments must simulate the behaviour of the cable constituents in controlled conditions. As reactants, they used either the commercially available product or a similar chemical composition. The reactant powders were ground together, placed in alumina or platinum crucibles and heated following the conditions summarized in Table 1.

Table 1: Interactivity of the cable constituents (Henrist, et al., 2000)

Reactants	Temperature of treatment [°C]	Identified products of reaction
Alumina trihydrate Zinc borate	900	$2ZnO.3B_2O_3.3,5H_2O + 4Al(OH)_3 \rightarrow 2ZnAl_2O_4 + 9,5H_2O + 3B_2O_3$
Zinc borate Silicon dioxide	1180	No reaction
Silicon dioxide Alumina trihydrate	1180	No reaction
	1400	$3Al_2O_3 + 2SiO_2 \rightarrow Al_6Si_2O_{13}$
Copper Alumina trihydrate	900	$Cu + 2Al(OH)_3 + 0,5O_2 \rightarrow CuAl_2O_4+3H_2O$ $2Cu + 2Al(OH)_3 + 0,5O_2 \rightarrow 2CuAlO_2 + 3H_2O$ $Cu + 0,5O_2 \rightarrow CuO$
Copper Alumina trihydrate Zinc borate	900	$2ZnO.3B_2O_3.3,5H_2O + 4Al(OH)_3 \rightarrow 2ZnAl_2O_4 + 9,5H_2O + 3B_2O_3$ $2Cu + O_2 + 2ZnO.3B_2O_3.3,5H_2O + 6Al(OH)_3 \rightarrow Cu_2A_{l6}B_4O_{17} + B_2O_3 +2ZnO + 12,5H_2O$
Copper oxide Boric acid	900	$3CuO + 2H_3BO_3 \rightarrow Cu_3B_2O_6 + 3H_2O$
Copper Zinc borate	950	Dendritic copper oxide No copper borate
Copper Zinc borate Silicon dioxide	900	Dendritic copper oxide No chemical association of Cu, Zn and Si

The cone calorimeter is likely to be adequate to address the fire hazard associated with fires and electrical cables in scenarios where cables are the main (or sole) combustibles. (Hirschler, 1994)

METHODS AND MATERIALS

The test samples were commercially available electric cable CHKE-V J3x1.5 PS60 B2ca with a total thickness of 9 mm produced by VUKI a.s.. The manufacturer states that it is a power cable with increased flame spread resistance. It is halogen-free, it meets the requirements for the B2ca fire reaction class (s1d1) and is functional in the fire for 180 minutes. It is designed for fixed placement in ordinary and humid environments. Cables can also be used in environments with a fire hazard and can be installed on flammable surfaces. (http://www.vuki.sk)

Aim of the paper was to evaluate time to ignition of the samples. Samples were exposed to external heat flow from cone calorimeter (Figure 1), with six different values: 25 kW m^{-2}, 30 kW m^{-2}, 35 kW m^{-2}, 40 kW m^{-2}, 45 kW m^{-2} and 50 kW m^{-2}. Samples were prepared by cutting the cable to 10 cm pieces and placed close to each other on 10 cm × 10 cm aluminium foil. Prepared sample (2) was inserted into the sample holder (1) and placed under the cone heater (4). Spark igniter (3) was located 13 mm above the sample. The resulting gaseous products of thermal decomposition of samples were aspirated by electric fan (6) through the hood of calorimeter (5). Initiation of the samples was monitored visually.

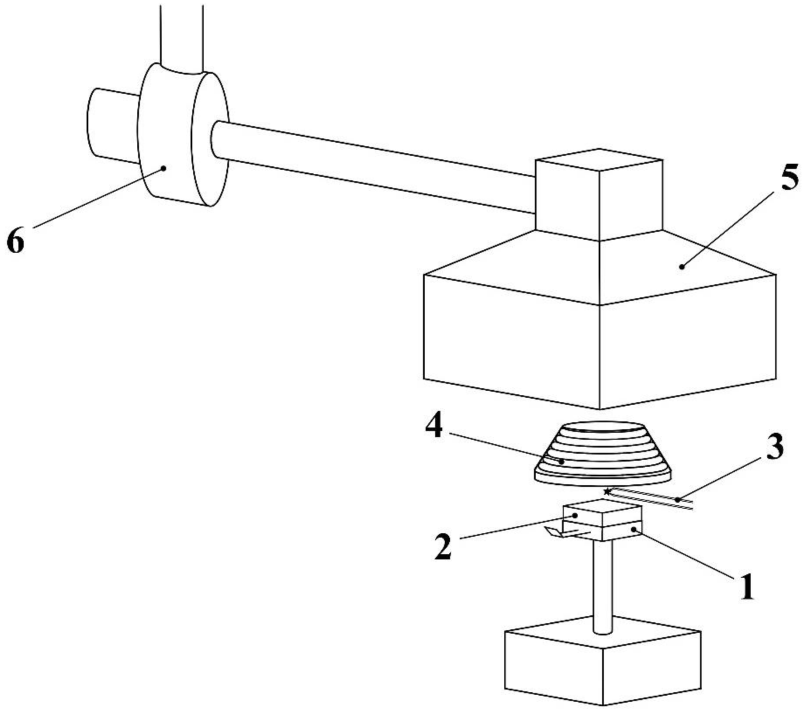

Fig. 1 *Test device: 1 – holder of sample, 2 – sample, 3 – spark igniter, 4 – cone heater, 5 – hood, 6 – fan (Rantuch et al., 2016)*

CRITICAL HEAT FLUX AND THERMAL RESPONSE PARAMETER

Critical heat flux is minimum heat flux at or below which there is no ignition, and thermal response parameter (TRP) should be defined as resistance to ignition and flame spread. It is a combination of ignition temperature above ambient, thermal conductivity, specific heat, and density of the material. Higher critical heat flux and TRP values suggest that materials are hard to ignite and have higher flame spread resistance. In general, thermosets have higher TRP values than the thermoplastics. (Tewarson, 1994) Typically, the critical heat flux values are determined by exposing the horizontal sample (e.g., about 100 mm diameter or about 100 mm x 100 mm square and up to about 100 mm in thickness with blackened surface in the flammability apparatus) to various external heat flux values until a value is found at which there is no ignition for about 15 min. The value of TRP for a surface that is not blackened is higher than the value for the blackened surface. (Tewarson, 2002)

The heat flux for the vertical orientation is averagely 15% higher than that for the horizontal orientation. This is caused primarily by the effect of concurrent direction of entrained air and pyrolysis gas flow for the vertically oriented samples, which significantly dilutes the flammable vapours. Therefore, to achieve enough concentration of flammable vapours for ignition, the critical heat flux for pilot ignition for vertical samples is higher. (Tsai, 2009)

Critical heat flux can be determined by calculation based on dependence of sample ignition time on external heat flux. This dependence can vary as each material has different parameters and characteristics. In Table 2, there is an overview of some identified relations for critical heat flux calculation for different materials.

Table 2: The dependence of external heat flux and time to ignition of sample

Function q_e	**Suitability of use**	**Source**
$q_e = f\left(\frac{1}{t_i^{\frac{2}{3}}}\right)$	Wood, pilot ignition	(Lawson, Simms, 1952)
	Thermally intermediate material	(Mikkola, Wichman, 1989)
$q_e = f\left(\frac{1}{t_i^{\frac{4}{5}}}\right)$	Wood, spontaneous ignition	(Lawson, Simms, 1952)
$q_e = f\left(\frac{1}{t_i^{\frac{1}{2}}}\right)$	Thermally thick material	(Mikkola, Wichman, 1989)
$q_e = f\left(\frac{1}{t_i}\right)$	For plasterboard: $30kW.m^2 \leq q_e \leq 40kW.m^2$ pilot ignition	(Bluhme, 1987)
	For wood: $20kW.m^{-2} \leq q_e \leq 30kW.m^{-2}$ pilot ignition	
	Thermally thin materials	(Mikkola, Wichman, 1989)
$q_e = f\left(\frac{1}{t_i^{0,547}}\right)$	Wood, piloted ignition	(Janssens, 1991)

According to Meinier et al. (2018) time to ignition of halogen-free flame retardant cables with an external diameter of 12 mm, is well predicted by the so-called thermally thick model considering only the sheath properties.

RESULTS AND DISCUSSION

The results of the time to ignition measurements together with the weight of the individual samples are shown in Table 3. The measured values show that with increasing heat flow, time to ignition decreases. This is a generally known fact that is caused by the increasing amount of thermal energy incident to the surface of the samples. This energy is divided into three components:

1. Component reflected to the environment, which depends on the emissivity of the sample
2. Component drawn into the interior of the sample, which depends on the thermal conductivity of the test material
3. Component absorbed by a thin surface layer, which depends on the thermal properties of the loaded material.

Due to the increasing temperature, thermal degradation of the surface layer and the release of gaseous flammable substances occurs. Upon reaching a sufficient temperature and concentration of their mixture with air, initiation of flame burning occurs.

Table 3: Measured values of time to ignition

Heat flux [kW m^{-2}]	Sample weight [g]	Time to initiation [s]
25	150.1	181
30	150.8	136
35	149.9	91
40	153.0	68
45	148.6	45
50	148.2	43

Based on relations shown in Table 2, graphs of corresponding dependencies were created (Fig. 2). Trend lines were plotted in each graph to evaluate the linear dependence of parameters. The relevant equations of linear regression and squares of correlation coefficients are shown in Table 4.

Table 4: Equations of trend lines and squares of correlation coefficients of various dependences of external heat flux and time to ignition

Function q_e	Linear regression equation	Square of correlation coefficient [-]
$q_e = f\left(\frac{1}{t_i^{\frac{2}{3}}}\right)$	y = 0.0021x - 0.0235	0.9924
$q_e = f\left(\frac{1}{t_i^{\frac{4}{5}}}\right)$	y = 0.0014x - 0.0215	0.9900
$q_e = f\left(\frac{1}{t_i^{\frac{1}{2}}}\right)$	y = 0.0033x - 0.0097	0.9940
$q_e = f\left(\frac{1}{t_i}\right)$	y = 0.0007x - 0.0143	0.9843
$q_e = f\left(\frac{1}{t_i^{0,547}}\right)$	y = 0.0029x - 0.0169	0.9937

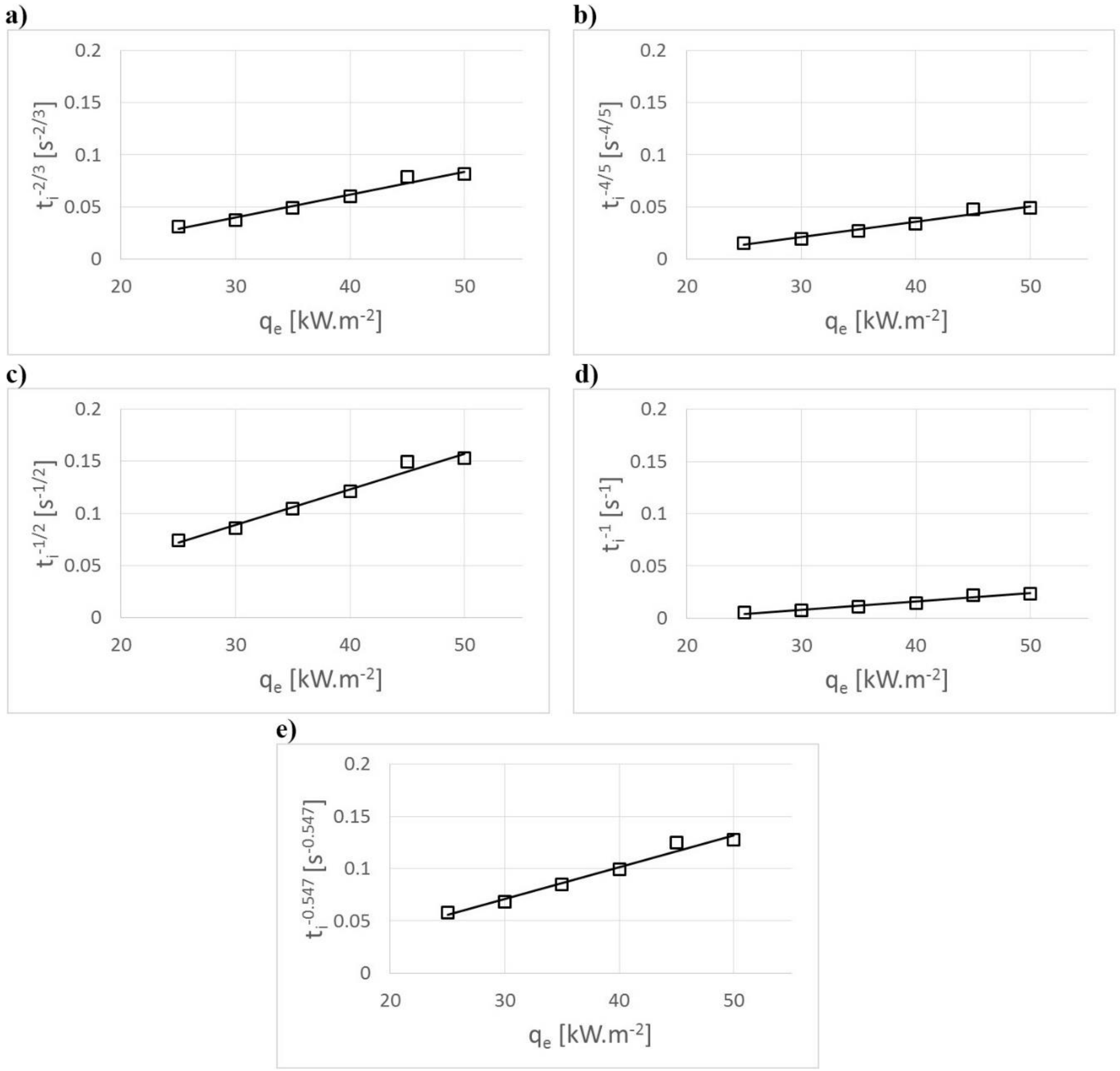

Fig. 2 *Graphs of various dependences of external heat flux and time to ignition: a)* $q_e\ vs\ t_i^{-\frac{2}{3}}$; b) $q_e\ vs\ t_i^{-\frac{4}{5}}$; c) $q_e\ vs\ t_i^{-\frac{1}{2}}$; d) $q_e\ vs\ t_i^{-1}$; d) $q_e\ vs\ t_i^{-0,547}$

Due to the suitability of various dependencies (Table 2) and squares of correlation coefficients (Table 4), the most appropriate dependence is $q_e\ vs\ t_i^{-\frac{1}{2}}$. Calculation of this dependence is used in the paper of Fateh et al. (2014). The basic equation takes the form:

$$t_i = \frac{\pi}{4} k\rho c \left(\frac{T_i - T_0}{q_e - q_{cr}}\right)^2, \qquad [1]$$

where t_i is time to ignition, k is thermal conductivity, ρ is density, c is heat capacity, T_i is ignition temperature, T_0 is ambient temperature, q_e is external heat flux and q_{cr} is critical heat flux. The equation can be further modified as follows:

$$TRP = (T_i - T_0)\sqrt{k\rho c} \tag{2}$$

$$\sqrt{\frac{1}{t_i}} = \frac{2}{\sqrt{\pi}}\frac{(q_e - q_{cr})}{TRP}, \tag{3}$$

where TRP is thermal response parameter. The values of critical heat flux and thermal response parameter can be calculated as:

$$q_{cr} = -\frac{TRP.y_{intercept}}{\sqrt{\frac{4}{\pi}}} \tag{4}$$

$$TRP = \sqrt{\frac{4}{\pi}}\frac{1}{Slope}, \tag{5}$$

where $y_{intercept}$ is interception of trend line with y-axis.
Delichatsios et al. (1991) developed equation, which relate the time to ignition to the imposed heat flux in standard flammability test measurements, where surface reradiation losses are significant:

$$\frac{1}{\sqrt{t_i}} = \frac{2}{\sqrt{\pi k\rho c}(T_i - T_0)}\left[q_e - 0{,}64q_{cr}\right]. \tag{6}$$

Calculated values of critical heat fluxes and thermal response parameters are shown in Table 5. In the table are also shown results from other authors to compare their findings. In the terms of critical heat flow, a relatively low value was observed for the investigated electrical cable, which is virtually identical to the polymethyl methacrylate tested by Rhodes and Quintiere (1996). In contrast, the thermal response parameter is very high compared to other materials. Therefore, it can be stated that flame spread resistance to of the tested cable is given by the value of its TRP.

Coutry and Garo (2017) tested two types of electric cables in the furnace of circular cross-section. Their values for the critical heat flux are twofold compared to the results of this study and the value of the thermal response parameter is about half of this study result. These differences can be caused by different insulation materials of the tested cables as well as another used methodology. While this study describes the effect of the heat flow on one side of more cables next to each other, mentioned authors studied effect of heat flux on the whole surface of single cable in a vertical position.

Table 5: Critical heat fluxes and thermal response parameters of various materials (* H – horizontal; V – vertical)

Material	**Orientation ***	**Critical heat flux [kW m^{-2}]**	**TRP [kW s$^{0.5}$ m^{-2}]**	**Equation**	**Source**
Electric cable	H	2.94	342	(1)	This study
Electric cable	H	4.59	342	(6)	This study
Plywood B	H	11	136	$t_i = \frac{\pi}{4} k\rho c \left(\frac{T_i - T_0}{q_e - q_{cr}}\right)^2$	(Fateh et al., 2014)
Plywood D	H	10.5	124		
PMMA	H	9.2	250.8	$t_i = \frac{\pi}{4} k\rho c \frac{(T_i - T_0)^2}{Q_R^2}$	(Tsai, 2009)
	V	10.4	268.7		
Polystyrene foam 10 mm	H	14.5	87.5		
	V	18.0	105.5		
Polystyrene foam 20 mm	H	7.2	108.5		
	V	17.4	122.7		
PMMA	H	4	–	$t_i = \frac{2}{3} k\rho c \frac{(T_i - T_0)^2}{q_{net}^2}$	(Rhodes, Quintiere, 1996)
Acrylic textile	H	9	–	$\frac{1}{t_i} = A.q_e + B$	(Nazare et al., 2002)
Heavy silk textile	H	12	–		
Wool textile	H	11	–		
Polyamide 6 nanocomposite	H	17.9	–	$t_i = \frac{\pi}{4} k\rho c \left(\frac{T_i - T_0}{q_e - 0.64 q_{cr}}\right)^2$	(Zhang et al., 2009)
Expanded polystyrene	H	11.77 –12.07	–	$t_i = \frac{\pi}{4} k\rho c \left(\frac{T_i - T_0}{\varepsilon . q_e}\right)^2$	(An et al., 2015)
Extruded polystyrene	H	10.42 – 10.82	–		
Polypropylene	H	–	291	$\sqrt{\frac{1}{t_i}} = \sqrt{\frac{4}{\pi}} \frac{q_e}{TRP}$	(Tewarson, 1994)
Epoxy resin	H	–	457		
Epoxy kevlar	H	–	169		
Polyvinyl ester	H	–	263		
EPR/HYPALON cable	V	9	166	$\sqrt{\frac{1}{t_i}} = \frac{(q_i - q_{cr})}{TRP}$	(Courty, Garo, 2017)
PVC/PVC cable	V	6.2	141		

CONCLUSION

The paper deals with the initiation characteristics of an electric cable suitable for installation in a fire hazardous environment and on a flammable substrate. Time to ignition of samples at different values of the external heat flux was monitored. With increasing heat flow, time to ignition raised from 43 seconds (50 kW m^{-2}) to 181 seconds (25 kW m^{-2}).

Based on the obtained data as well as the use of various functions describing the dependence of external heat flux and time to ignition, external thermal flux and thermal response parameter were calculated. These two variables describe the behaviour of the materials in the initiation phase of the fire.

The calculated value of the external heat flux in dependence on the calculation method was 2.94 kW m^{-2} or 4.59 kW m^{-2} respectively. The value of the thermal response parameter was 342 kW s$^{-0.5}$ m^{-2}. According to these results, the flame spread resistance of the test cable is most dependent on its TRP value.

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