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Study on Combustion Characteristics of Cable Based on Cone Calorimeter

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Abstract: Cross-linked polyethylene (XLPE) carries a high fire risk. In this paper, a cone calorimeter is used to carry out radiation ignition experiments, and the heat release rate (HRR), mass loss rate (MLR) and other combustion parameters of XLPE cables under three kinds of radiation intensity are measured. By comparing the ignition time and HRR of samples under different conditions, the following conclusions are drawn: (1) The ignition time of XLPE cables decreases significantly with the increase in external thermal radiation intensity. The critical ignition heat flux (CHF) is about 16.24 kW/m². (2) The HRR curve of XLPE is consistent with the characteristics of hot, thick material. The HRR rises rapidly to the first peak after ignition and then rapidly decreases. Then, it slowly rises to the second peak. Finally, it slowly decays until the combustion stops. (3) The first peak values of HRR of XLPE under different radiation intensities are almost the same. The time for the second peak of HRR is shorter, and the value is larger with the increase in external thermal radiation intensity. (4) The cable ignition model is established, which can simulate the cable ignition time well under different radiant heat flow conditions. (5) Based on the mathematical model, the ignition time trend with the thickness of sheath layer and conductive core layer as variables is deduced.



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Keywords: cone calorimeter; cable; XLPE; ignition time; HRR

1. Introduction

With the increasing demand for electric energy in social and economic sectors and industrial production, the use of cables has increased significantly. However, power cables with flammable insulation have been considered to be non-negligible potential fire sources. Fires related to electrical cables have occurred occasionally, resulting in a large number of casualties, major property losses and a serious negative social impact [1]. Therefore, the combustion characteristics of cable materials have been regarded as hot issues.

The cone calorimeter is a laboratory-scale device that has been proven to be useful in the estimation of full-scale fire behaviors of various products, such as cables [2–4]. Hirschler [5] and Barnes [6,7] used a cone calorimeter to study the combustion behaviors of a series of cables based on ISO 5660 and ASTM d5424 [8]. During the experiments, these cables had the same layout, but the sheath or insulation composition was different. The results showed that the peak values of HRR data were basically consistent under the two standard methods. Coaker et al. [9] found that for various cables containing vinyl compounds, the full-size cable tray test and cone calorimeter had good correlation in terms of heat and smoke release. Especially under the condition of 20 kW/m² external radiant heat flux, the correlation was good. Therefore, most scholars believe that the use of a conical calorimeter is a very standard experiment to study cable fire behavior [10].

Cable structure and layout are important parameters affecting fire development and fire risk. However, few papers can be found in the literature based on the use of a cone calorimeter to detect the heat conduction process of cables. Cables are mainly composed

of conductors, insulation and sheaths. Among them, the most important factors affecting the combustion characteristics of a cable are insulation and sheath materials [11]. Some scholars used a cone calorimeter to study the combustion characteristics of PVC cables and obtain fire characteristics such as ignition time, heat release rate, mass loss rate, smoke generation rate and so on. It was found that the structure of PVC cables affected the ignition time [12–14]. At present, no article has studied the heat conduction process of XLPE cables. The maximum working temperature of XLPE cables does not exceed 90 °C, while that of PVC cables is 70 °C. At the same time, the insulation performance of XLPE cables is better than that of PVC cables [15].

Based on cone calorimeters, the influence laws of external heat flux intensity, cable spacing, cable insulation thickness and other factors on cable ignition characteristics can be carried out [16–19]. The results show that increasing the thickness of the sheath will also have a negative impact on the fire resistance of a cable. All these parameters will affect the HRR curve of cable combustion. Therefore, the parameter design for different thickness and radiation intensity can be solved by establishing a mathematical model. However, the influence of the thickness of the sheath layer and conductor core layer on ignition time has not been studied.

In conclusion, the cone calorimeter has been recognized as an important tool to measure the ignition characteristics of various cable materials. By changing the test conditions, heat flux and the influence of cable flammability are studied in this paper [20,21]. The heat release rate (HRR), mass loss rate (MLR) and other combustion parameters of XLPE cables under different radiation intensities are measured. Then, the ignition time and HRR of XLPE cable materials under different external radiation heat fluxes are analyzed, and the critical heat flux for ignition (CHF) is calculated. Finally, the cable ignition model is established based on the heat conduction theory. Based on the ignition model, the ignition law, with the thickness of the sheath layer and core layer as variables, is analyzed. The conclusions of this paper can provide supporting data for the follow-up study of the fire spread process in XLPE cables.

2. Experiments

2.1. Experimental Setup

For cable fires, the local sharp temperature rise caused by its own short circuit, excessive load and other reasons causes the decomposition, degradation and combustion of the cable sheath, which aggravates the temperature rise in a cable and cause a fire. Generally, a cable is composed of a sheath layer and a conductive core layer, as shown in Figure 1. In experiments using a cone calorimeter, the cable is generally divided into three layers: the upper sheath layer, core layer and lower sheath layer. The physical parameters of the cable in this experiment were as follows: the cable diameter was 9 mm, the thickness of the sheath layer was 2 mm and the thickness of the conductive core layer was 5 mm.

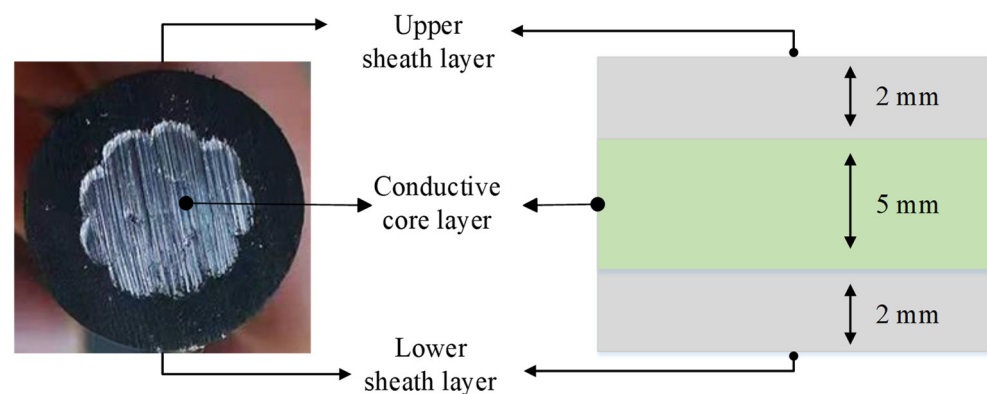


Figure 1. Cable structure.

The experiments were based on the ISO 5660 standard [8]. Three different radiation intensities [22] (20 kW/m^2 , 30 kW/m^2 and 40 kW/m^2) were set up to carry out radiation ignition experiments on XLPE. In order to reflect the repeatability of the experiments and eliminate the influence of environmental factors, three repeated experiments were carried out under each radiation intensity. XLPE cables with a diameter of 9 mm were processed into cable segments with lengths of 10 mm. Eleven cables were closely arranged in a tray, as shown in Figure 2. All experimental conditions are summarized in Table 1.



Figure 2. Cable arrangement.

Table 1. XLPE radiation ignition condition setting and numbering.

Case	Material	Size/(cm ³)	Mass/(g)	Radiation Intensities/(kW/m ²)	Calibration Temperature/(°C)
20#1	XLPE	10 × 10 × 1.5	185	20	427.3
20#2	XLPE	10 × 10 × 1.5	189	20	427.3
20#3	XLPE	10 × 10 × 1.5	183	20	427.3
30#1	XLPE	10 × 10 × 1.5	187	30	531.2
30#2	XLPE	10 × 10 × 1.5	185	30	531.2
30#3	XLPE	10 × 10 × 1.5	188	30	531.2
40#1	XLPE	10 × 10 × 1.5	188	40	569.8
40#2	XLPE	10 × 10 × 1.5	183	40	569.8
40#3	XLPE	10 × 10 × 1.5	186	40	569.8

2.2. Experimental Equipment

A cone calorimeter, a piece of radiation ignition experimental equipment, is composed of a radiation ignition platform, gas analyzer and computer processor, as shown in Figure 3 [2,23]. The radiation ignition platform mainly consists of a heating radiation cone, weighing equipment, a smoke-collecting hood, igniter and a heat flow meter. The radiation heat flux intensity of a radiation cone is calibrated by a heat flux meter. After a sample receives the uniform heat flux of the radiation cone to decompose the combustible gas, the spark ignition igniter is used to ignite the sample. The weighing equipment can record the mass change of the sample in the combustion process. The smoke-collecting hood is used to collect the smoke generated. The gas analyzer can analyze the volume fraction of each type of gas in the smoke through the sensor set in the exhaust duct and calculate the

HRR of materials after combustion by using the oxygen content in the smoke. A computer processor is used to control the operation of the equipment and the storage and processing of the experimental data.



Figure 3. Cone calorimeter.

In the early 1980s, in order to solve the problem of the lack of small heat release test capability, the NIST laboratory in the United States developed a cone calorimeter based on the principle of oxygen consumption [8]. About 17.2 MJ of heat is released for every 1 m³ of oxygen consumed, and the accuracy is within 5%. The heat release rate of the material is calculated as follows:

$$HRR = H_{O_2} \dot{m}_{O_2}^0 \phi \quad (1)$$

where ϕ is the oxygen consumption factor, H_{O_2} is heat of combustion of oxygen, and $\dot{m}_{O_2}^0$ is the oxygen mass flow in per unit time. The calculation equation of oxygen consumption factor is as follows:

$$\phi = \frac{(X_{O_2}^0 - X_{O_2})}{X_{O_2}^0 (1 - X_{O_2})} \quad (2)$$

where $X_{O_2}^0$ is the mole fraction of oxygen in the air, and X_{O_2} is the mole fraction of oxygen measured in the experiment. The mass flow of oxygen into the system is as follows:

$$\dot{m}_{O_2}^0 = X_{O_2} \left(1 - X_{CO_2}^0 - X_{H_2O}^0 \right) \frac{M_{O_2}}{M_{air}} \frac{1}{1 + \phi(\alpha - 1)} C \sqrt{\frac{\Delta P}{T_\infty}} \quad (3)$$

where X_{CO_2} is the mole fraction of carbon dioxide, X_{H_2O} is the mole fraction of water vapor, M_{O_2} is the molar mass of oxygen, M_{air} is the molar mass of air, and α is the air expansion factor after oxygen is completely consumed. C is the pipe constant, T_∞ is the temperature of the gas in the pipe, and ΔP is the pressure difference. By substituting the above equation into (1), the formula for measuring heat release rate of the cone calorimeter can be obtained:

$$HRR = H_{O_2} X_{O_2}^0 \left(1 - X_{CO_2}^0 - X_{H_2O}^0 \right) \frac{M_{O_2}}{M_{air}} \frac{\phi}{1 + \phi(\alpha - 1)} C \sqrt{\frac{\Delta P}{T_S}} \quad (4)$$

2.3. Experimental Process

Before carrying out the experiments, the weighing equipment, gas analyzer and radiation cone of the cone calorimeter were calibrated in turn. From top to bottom, the sample tray consisted of a sample clip, XLPE sample and mineral wool cushion. After the calibration of the equipment, the air pump was turned on, and the initial mass of the sample was measured by the weighing equipment. Then, the radiation cone heating device was turned on. During this process, the insulation baffle was opened to prevent the sample

from being thermally radiated in advance. The radiation intensity remained constant after reaching the preset value. After 60 s baseline data were collected, the heat shield was removed. The sample then began to receive the radiation heat flux from the radiation cone. In order to prevent the measurement error, the electric spark ignition device was used to ignite the sample surface while the heat shield was removed. When the sample was ignited, the ignition device was removed. The experimental data and combustion phenomena were observed and recorded. At the end of the experiment, the radiation cone was turned off. The combustion of XLPE under different radiation intensity could be measured by the following two parameters:

- (1) Ignition time: The time when the sample received external heat flow was recorded as time 0. The time when the sample appeared as a continuous flame was recorded as the ignition time. The ignition time of the sample was determined by the experimental video recorded by the camera. In order to avoid too much combustible gas produced by the pyrolysis of materials in the process of radiation heating, it was necessary to use an electric spark igniter for continuous ignition.
- (2) Heat release rate: The calculation of HRR using a cone calorimeter was based on the principle of oxygen consumption. The combustion characteristics of materials in different combustion stages could be summed up by analyzing the HRR–time curves obtained from the cone calorimeter.

3. Results and Discussion

Through experiments, the ignition data of XLPE cables under different radiation intensities were obtained. The data of HRR, MLR of pyrolysis and combustion, ignition time and combustion phenomenon were recorded. The discussion and comparative analysis of the main experimental results follows.

3.1. Analysis of Ignition Time and CHF

Ignition time is an important parameter for judging the ignition performance of solid polymer. The ignition time is mainly determined by the thermophysical parameters of polymer materials and the strength of the external heat source. The specific parameters are mainly reflected in the thermal reaction parameter (TRP) and critical heat flow for ignition (CHF). The CHF is calculated by ignition time (t_{ig}) determined by radiation ignition experiments. The formula of CHF and TRP is as follows:

$$\frac{1}{t_{ig}} = \frac{\dot{q}_e'' - \text{CHF}}{\text{TRP}} \quad (5)$$

where t_{ig} is ignition time, and $\dot{q}_e''$ is external radiation.

The ignition time of the radiation ignition of XLPE cable samples under different external heat fluxes is shown in Table 2. When the external thermal radiation intensity is 20 kW/m², the average ignition time is about 83.5 s. When the external thermal radiation intensity is 30 kW/m², the ignition time is greatly shortened, and the average value is about 25 s. The average ignition time further decreases to about 13.3 s when the external heat flux reaches 40 kW/m². This indicates that the external thermal radiation intensity has a great influence on the ignition characteristics of XLPE. The thermal decomposition of XLPE is accelerated at higher radiation intensities. The material decomposes after heating to produce combustible gas and flaming combustion occurs. The average error of measurement is 13.3%.

The CHF of XLPE can be estimated roughly by ignition time according to the theoretical basis. According to Formula (5), the scatter plot is drawn with the reciprocal of ignition time as the ordinate and the external heat flux as the abscissa. Then, the curve shown in Figure 4 is obtained by linear fitting. The external heat flux of material is CHF when the ignition time is infinite ($1/t_{ig} \propto 0$). The intersection of the fitting line and the abscissa on the scatter plot is CHF. The slope of the fitting line is the reciprocal of the thermal

reaction parameters ($1/\text{TRP}$). The linear fitting formula of the average ignition time of XLPE under three different external radiation intensities is given in the figure. The correlation coefficient of fitting line is 0.99. The calculated values of CHF and TRP are 16.24 kW/m^2 and $325.7 \text{ kW}\cdot\text{s}^{1/2}/\text{m}^2$, respectively. The vertical error bars for this set of the data indicate the range of levels in the three tests, which are not more than 9.8%. The figure compares the radiation ignition time relationship data of Wang [12] and Meinier's [14] for PVC cables. It can be seen from the figure that the slope of the XLPE cable is higher than that of the PVC cable, indicating that the XLPE cable is better than the PVC cable in terms of fire resistance.

Table 2. Ignition time of XLPE cables under different radiation intensities.

Radiation Intensities/(kW/m ²)	Experimental Value			Average Value (s)
	#1 (s)	#2 (s)	#3 (s)	
40	16	13	11	13.3
30	26	20	29	25
20	85	92	79	83.5

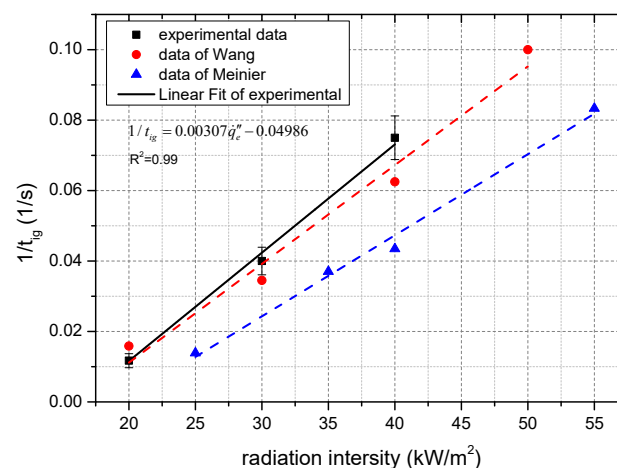


Figure 4. XLPE ($1/t_{ig}$) and external heat flux diagram.

3.2. Analysis of HRR

The HRR is another important parameter used to measure the burning intensity of materials. The XLPE used in the experiments was thermally thick. Thermally thick fuels can be approximated as having spatial and internal temperature gradients, while thermally thin fuels do not [24,25]. The peak value of the HRR in the combustion process is higher than that of thermally thin fuels, and the duration of combustion is relatively longer. In this paper, the risk of cables in fire is analyzed through the change of the HRR value of XLPE in the combustion process.

It can be seen from Figure 5a that the change trend of heat release rate of the three experiments is basically the same when the external thermal radiation is 20 kW/m^2 . This shows that the experiment has good repeatability. The HRR of the samples display a steep rise at about 80 s. The samples were ignited at that time. This is close to the ignition time (85 s) observed in Section 3.1. The HRR of XLPE cable rises rapidly after being exposed to thermal radiation. The reason for this is that cross-linked polyethylene belongs to high-molecular polymer, and combustible gas will be rapidly precipitated on the surface under high temperatures, resulting in flame combustion. The HRR reaches the first peak (about 270 kW/m^2) at about 100 s (15–20 s after ignition). Then, the HRR decreases sharply. This is due to the fact that the fiber inside the polymer is pyrolyzed to form a carbonization layer, which prevents the heat flow from further transferring to the polymer. The value of the HRR is reduced to about 85 kW/m^2 at about 250 s. Then, it increases slowly and reaches the second peak (about 150 kW/m^2) at about 800 s. The second peak appears because the carbonized layer on the polymer surface is gradually pyrolyzed under the continuous

thermal radiation. The heat flux is further transferred to the interior of the polymer, and the combustible gas is ignited after precipitating from the interior of the polymer and the carbonization layer. The HRR curve of the three experiments shows a similar trend in the combustion decay stage of XLPE. The HRR fluctuates in a certain range with the continuous formation and pyrolysis of the carbonized layer, but the overall trend continues to decline. The continuous decrease in the HRR is due to the decrease in pyrolytic materials with the loss of polymer mass. Additionally, the combustion of the material gradually changes from flaming combustion to flameless combustion until the combustion stops completely.

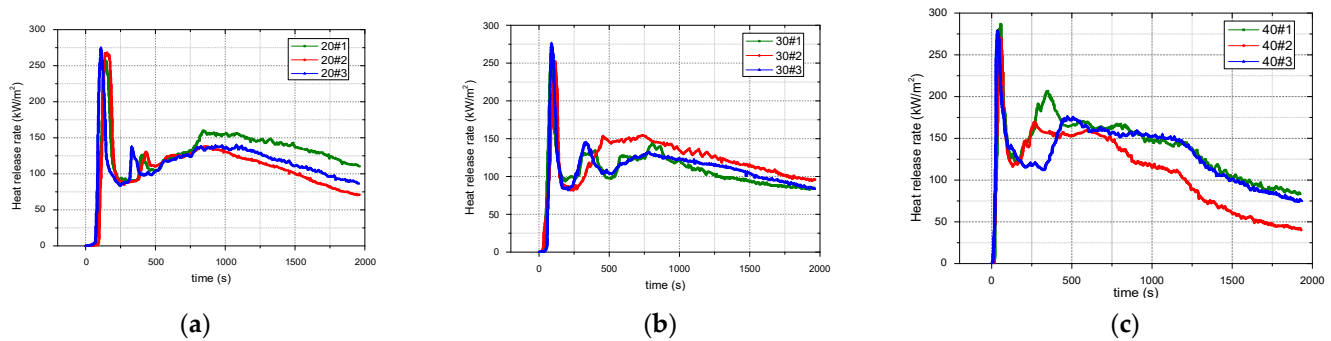


Figure 5. HRR curves of XLPE cables under different radiation intensities. (a) 20 kW/m², (b) 30 kW/m², (c) 40 kW/m².

The HRR curve of XLPE, shown in Figure 5b, still shows the characteristics of a typical thermal thick material when the external radiation intensities reaches 30 kW/m². The overall trend is the same as Figure 5a. First, it rises rapidly to reach the first peak, and then decreases rapidly. Subsequently, it slowly rises to the second peak. Finally, it shows a slow decay until the thermal decomposition stops completely. There is a certain deviation in the occurrence time of the second peak of the HRR in the three repeatability experiments. The time that the second peak appears for 30#1 and 30#3 is basically the same, but that for 30#2 is relatively later. It is possible that the thickness of the carbonized layer was different in the two experiments, which led to a certain deviation in pyrolysis time. The specific reason for this needs further study on the carbonization behavior of XLPE during heating, which is beyond the scope of this paper.

The curves of the HRR in the three repeated experiments shown in Figure 5c are basically the same when the external radiation intensities further increases to 40 kW/m². The overall change trend is similar to that of the first two groups (20 kW/m² and 30 kW/m²). The first peak of HRR appears at about 30 s (about 25 s after ignition). Then, it decreases rapidly to 125 kW/m² in 200 s before gradually rising. The occurrence time of the second peak of 40#1, 40#2 and 40#2 are not exactly the same, but the trends are consistent. The HRR of 40#2 is relatively low in the stage of combustion decay, which possibly related to the thermal decomposition of the carbonized layer.

3.3. Comparative Analysis of HRR of Different Radiation Intensities

By comparing the HRR curves of XLPE (shown in Figure 6) under three different radiation intensities, the following conclusions can be obtained:

- (1) The ignition time of XLPE decreases significantly with the increase in external thermal radiation intensity. The ignition time is about 85 s when the external radiation intensity is 20 kW/m². However, the ignition time is reduced to about 13 s when the external radiation intensity increases 40 kW/m². Yang [26] proved through experiments that under the condition of large external heat flow, the thermal decomposition of polymer materials is more rapid. The concentration of combustible gas reaches the lower limit of combustion in a short time. Then, it is ignited when encountering an electric spark.
- (2) The first peak values of HRR of XLPE under different radiation intensities are almost the same. The values of three groups range from 250 to 275 kW/m². This is due

to the fact that the peak value of heat release rate and material combustion only depend on the beginning and final state of chemical reaction. The radiation ignition experiments are carried out under the condition of sufficient oxygen, which belongs to the fuel-controlled combustion. The initial and final states of the reaction are the same after the carbonization layer is formed. Therefore, the first peak values of HRR for XLPE under different radiation intensities are almost the same.

- (3) The time and value of the second peak appears are different under different radiation intensities. It can be seen from Figure 6 that with the increase in external heat flux, the faster the HRR of XLPE reaches the second peak, and the greater the value is. The time of second peak appears is about 800 s, 700 s and 300 s, respectively, when the external radiation intensities are 20 kW/m², 30 kW/m² and 40 kW/m². The HRR values of the second peak are about 130 kW/m², 150 kW/m² and 200 kW/m², respectively. The carbonization layer formed by the combustion of fiber in the polymer needs a high temperature for pyrolysis. In the case of low external radiation intensities, the pyrolysis thickness of the carbonized layer is limited, and less combustible gas is produced, resulting in a lower value of the second peak. However, the larger external radiation intensity makes the pyrolysis temperature of the carbonized layer higher. More carbonized layers are pyrolyzed and higher combustion heat is generated, resulting in a higher value of the second peak of HRR [2,26].

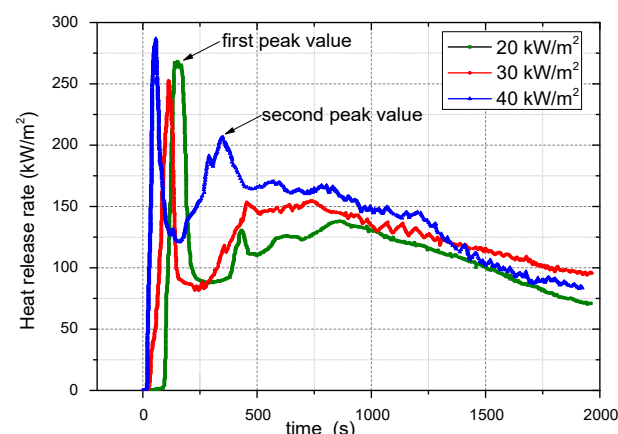


Figure 6. Comparison of HRR curves of XLPE cables under different radiation intensities.

3.4. Establishment of Cable Ignition Model Based on Heat Conduction

For the cable test sample using a cone calorimeter, the side and bottom of the sample are basically in an adiabatic state because the back and side are wrapped with a layer of glass fiber cloth with low thermal conductivity. Aluminum foil is coated on the outside of the glass fiber cloth to reduce the thermal radiation on the side, so that only the twisted surface of the cable test sample is exposed to the external radiant heat source. Therefore, it can be simplified to a one-dimensional heat transfer problem. The initial temperature of the cable test sample is the ambient temperature. Under the radiation of external heat source, the surface temperature of the cable sample increases with time, and there is convective heat loss and radiant heat loss on the upper surface of cable. This problem is a one-dimensional transient heat conduction process with finite thickness. When the surface temperature of the cable reaches the ignition temperature t_{ig} , the cable is considered to be ignited.

Figure 7 shows the simplified model of the cable under the cone calorimeter condition. The cable test sample is divided into the following three areas [12,27]: (1) upper sheath layer $0 < x < L_1$; (2) conductive core layer $L_1 < x < L_2$; (3) lower sheath layer $L_2 < x < L_3$.

The main assumptions of the model are as follows:

- (1) Only the upper surface of the cable is exposed to the external radiant heat flow, and the convective heat loss and radiant heat loss caused by the increase in surface temperature is considered.
- (2) The heat transfer inside the cable is one-dimensional transient heat conduction.

- (3) When the material surface reaches the critical temperature t_{ig} , the material is ignited.
- (4) There is no heat loss in the process of energy transfer between layers.

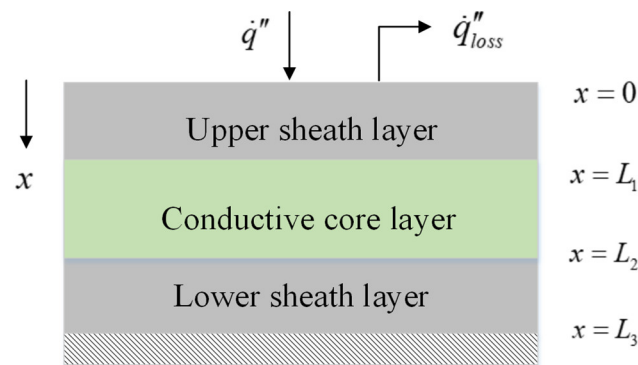


Figure 7. Schematic diagram of simplified cable model.

According to the physical model described above, the governing equations are established as follows [28]:

Energy conservation equation:

Upper sheath layer:

$$\rho_1 c_1 \frac{\partial T_1}{\partial t} = k_1 \frac{\partial^2 T_1}{\partial x^2} (0 < x < L_1) \quad (6)$$

Conductive core layer:

$$\rho_2 c_2 \frac{\partial T_2}{\partial t} = k_2 \frac{\partial^2 T_2}{\partial x^2} (L_1 < x < L_2) \quad (7)$$

Lower sheath layer:

$$\rho_3 c_3 \frac{\partial T_3}{\partial t} = k_3 \frac{\partial^2 T_3}{\partial x^2} (L_2 < x < L_3) \quad (8)$$

Boundary conditions:

$$x = 0, -k_1 \frac{\partial T_1}{\partial x} = \dot{q}'' - \dot{q}_{loss}'' = \dot{q}'' - h_c(T_s - T_\infty) - \varepsilon \sigma (T_s^4 - T_\infty^4) \quad (9)$$

$$x = L_1, -k_1 \frac{\partial T_1}{\partial x} \Big|_{x=L_1} = -k_2 \frac{\partial T_2}{\partial x} \Big|_{x=L_1}, T_1(L_1, t) = T_2(L_1, t) \quad (10)$$

$$x = L_2, -k_2 \frac{\partial T_2}{\partial x} \Big|_{x=L_2} = -k_1 \frac{\partial T_3}{\partial x} \Big|_{x=L_2}, T_2(L_2, t) = T_3(L_2, t) \quad (11)$$

$$x = L_3, -k_1 \frac{\partial T_3}{\partial x} = 0 \quad (12)$$

Initial conditions: $T(x, 0) = T_\infty$

Where T_1 , T_2 and T_3 are the temperatures of the upper sheath layer, the core layer and the lower sheath layer, respectively, K. The cables used in the experiment are self-developed cross-linked polyethylene cables [29]. $\rho_1 = \rho_3$ is the density of the sheath layer, 920 kg/m³. ρ_2 is the density of the core layer, 2430 kg/m³. $k_1 = k_3$ is the thermal conductivity of the sheath, 0.4 W/(m·K). k_2 is the thermal conductivity of the core, 180 W/(m·K). $\dot{q}''$ is the external radiant heat flux W/m², and $\dot{q}_{loss}''$ is the surface convective heat loss and radiant heat loss W/m². ε is the surface emissivity, and σ is the Stephen Boltzmann constant, 5.67×10^{-8} W/m²K⁴. T_s is the surface temperature of the cable sample, K. T_∞ is the ambient temperature, K.

In the cable ignition model, both the upper surface boundary and the coupling boundary between layers are nonlinear boundary conditions, and the analytical solution of the equation cannot be obtained. Therefore, the Gauss Seidel iterative method is used to solve the model.

Figure 8 shows the comparison between experimental ignition time and model calculation time under various working conditions. It can be seen from the table that under high heat flux, the cable surface temperature rises rapidly, and the ignition time is very short. When the surface temperature reaches the ignition temperature, the heat has not been or only a small amount has been transferred to the core layer, so the ignition time of the model is lower than that of the experiment. At low heat flux, the heat is transmitted to the core layer through the sheath layer, and the surface temperature rises more and more slowly, which makes the ignition time of the model longer than the experimental time. However, the calculated results of the model basically match the experimental results. The mean absolute percentage error between the model value and the experimental average value is 11.17%.

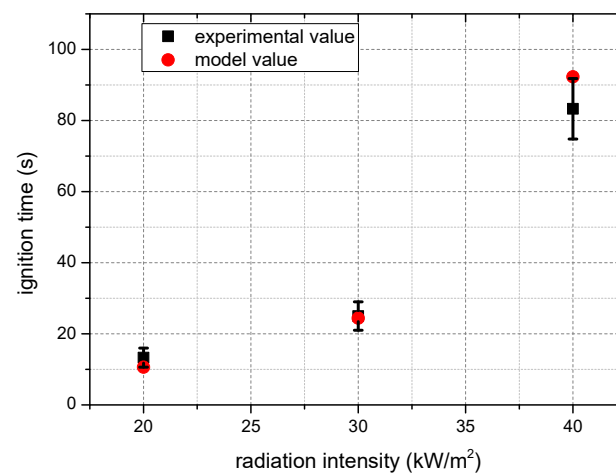


Figure 8. Comparison of cable ignition time.

3.5. Derivation of Cable Ignition Characteristics Based on Model

Based on the model, the radiation ignition time curve, with the thickness of the sheath layer and conductive core layer as variables, is further deduced. Figure 9 shows the ignition time variation curve of the thickness of the sheath layer ranging from 0.1 mm to 4 mm (the thickness of the core layer is 5 mm). It can be seen from the figure that when the sheath layer is very thin, the cable is mainly composed of the conductive core layer. The heat conductivity of metal is very high, so the surface temperature rises slowly, and the ignition time is relatively long. When the sheath layer thickens gradually, the temperature gradient in the sheath layer increases gradually, so the ignition time decreases gradually. When the thickness of the sheath layer increases to a certain extent, the heat has not been transmitted to the conductive core layer at the time of cable ignition, so the ignition time remains a fixed value and is no longer related to the thickness. By fitting the data, it is found that there is a Boltzmann function relationship between ignition time and sheath thickness. The data-fitting formula is given in the figure, and R^2 is greater than 0.99.

Figure 10 shows the variation curve of ignition time in the range of conductive core layer thickness from 0.1 mm to 6 mm (the thickness of sheath layer is 2 mm). It can be seen from the figure that when the thickness of the conductive core layer approaches 0, the cable considers that there is no conductive core layer, only the sheath layer. With the increase in the thickness of the conductive cable core layer, the conductive core layer will delay the rise of the temperature of the sheath layer. The thicker the core layer of the cable, the slower the temperature rise of the surface sheath layer, resulting in the longer ignition time of the cable. By fitting the data, it is found that there is an exponential function relationship

between ignition time and conductive core thickness. The data fitting formula is given in the figure, and R^2 is greater than 0.99.

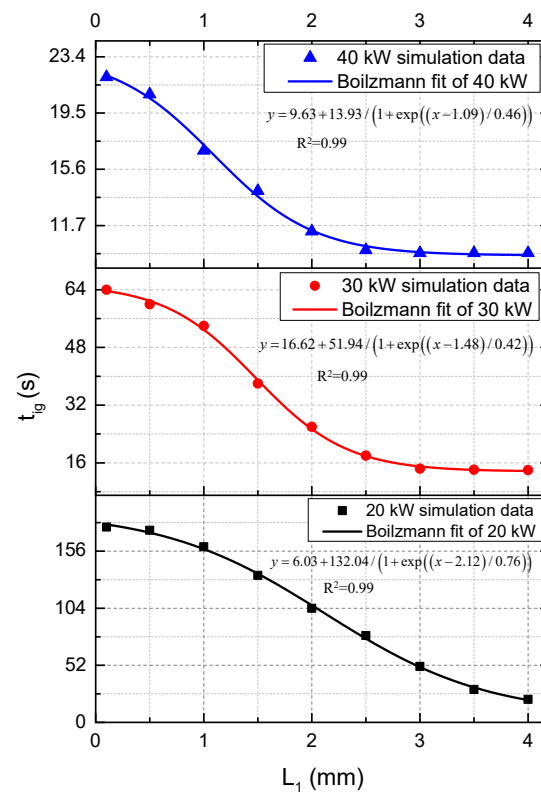


Figure 9. Influence of sheath thickness on ignition time.

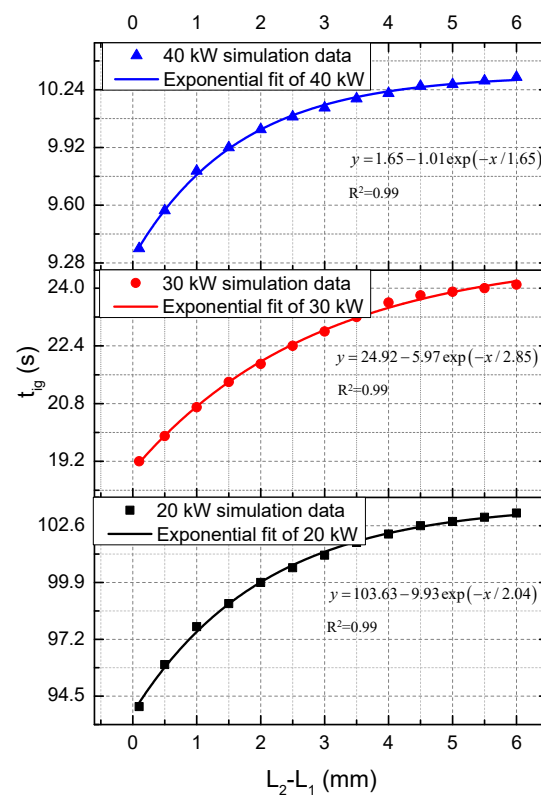


Figure 10. Influence of cable core thickness on ignition time.

4. Conclusions

The radiation ignition experiments on XLPE cable material were carried out using a cone calorimeter, and the changes of ignition time and HRR under different external radiation intensities were analyzed. Three different external radiation intensities (20 kW/m², 30 kW/m² and 40 kW/m²) were set up. The experiment was carried out three times under each radiation intensity. The main conclusions are as follows: (1) The ignition time of XLPE cables decreases significantly with the increase in external thermal radiation intensity. The critical ignition heat flux (CHF) is about 16.24 kW/m². (2) The heat release rate curve of XLPE is consistent with the characteristics of hot, thick material. The HRR rises rapidly to the first peak after ignition and then rapidly decreases. Then, it slowly rises to the second peak. Finally, it slowly decays until the combustion stops. (3) The first peak values of HRR of XLPE under different radiation intensities are almost the same. The time for the second peak of HRR is shorter, and the value is larger with the increase in external thermal radiation intensity. (4) The upper and lower boundaries and initial conditions of the cable ignition model are established by using the energy conservation equation, and the Gauss Seidel iterative method is used to solve the equations. The model can simulate the cable ignition time well under different radiant heat flow conditions and can verify the rationality of the cable ignition model. (5) As the sheath layer of the cable becomes thicker, the ignition time becomes shorter, and the ignition time has a Boltzmann function relationship with the thickness of the sheath layer. As the conductive core layer becomes thicker, the ignition time becomes longer, and the ignition time has an exponential function relationship with the thickness of the conductive core layer.

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