Ignition of Energized PVC-Insulated Electrical Wires and Characteristics of Smoke Particles Formed during Combustion


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ABSTRACT

Ignition of energized polyvinyl chloride (PVC) insulated copper wires by external heating has been investigated to better understand the initiation of electrical-wire fires. Experiments on three kinds of sample wires have shown that the ignition time concavely decreases with the increasing external heat flux, while convexly decreasing with the increasing current of wire. The properties of fire and pyrolysis smoke particles were studied through Transmission Electron Microscope (TEM), Scanning Electron Microscope (SEM) and fast particulate spectrometer (FPS). The fire smoke particles have been found independent to the current of wire and to show the same morphology as standard test fires. The properties of pyrolysis smoke particles showed a two-regime behavior with the increasing current of wire. The pyrolysis smoke particle size distribution with one certain current showed well fitted by a lognormal distribution. The three-stage change of the count median diameter (CMD) and geometry mean diameter (GMD) versus time has also been studied.

KEYWORDS: Electric current, electrical wire, ignition time, smoke particle.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>CMD</td>
<td>count median diameter (nm)</td>
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<tr>
<td>GMD</td>
<td>geometry mean diameter (nm)</td>
</tr>
<tr>
<td>I_{ch}</td>
<td>electric current of coil heater (A)</td>
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<tr>
<td>I_{w}</td>
<td>electric current of wire (A)</td>
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<td>SPNC</td>
<td>smoke particle number concentration (cm⁻³)</td>
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Subscripts

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<tr>
<th>Subscript</th>
<th>Description</th>
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<tbody>
<tr>
<td>ch</td>
<td>coil heater</td>
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<tr>
<td>w</td>
<td>wire</td>
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INTRODUCTION

With the accelerating pace of urbanization and electrification, the incidence of electrical fires is increasing. From 2009 to 2011, an estimated 25900 residential building electrical fires were reported by U.S. fire departments annually [1]. 48.3% of the items first ignited in these fires were electrical wires. In nuclear power plants, electrical wire is a major source of fire ignition, consisting of 42% of total fires [2]. Most electrical fires are caused by short circuit, overheating and worn wire with the ignition of insulation attached to the wires [3, 4]. Once ignited, fires might propagate along the wire and ignite nearby combustibles, releasing heat, smoke and toxic gases.

Polyvinyl chloride (PVC) is the most common insulation material used for wiring in low-voltage service, comprising about two-thirds of the insulation used for building wiring in the USA [5, 6]. The immense number of electrical wires in use is the main cause of electrical fires. Although the PVC insulation is flame retardant, it could catch fire and generate soot when exposed to a continuous external heat source. With Joule heating from the current flowing through the wire, the pyrolysis of PVC insulation can occur, followed by white smoke released without flame.
In recent years, various tests have been developed to study the ignition time of electrical wires, which is an important parameter of early fire detection. Leung et al. [7] simulated the effect of the central conductor on thermal pyrolysis of the insulation layer without flame during the heating process. Fujita [8], Nakamura [9], Huang [10] et al. experimentally studied the effects of oxygen concentration, ambient pressure, wire size, inclinations and gravity on the ignition of PE insulated wires, and established an ignition model of externally heated wires systematically. Cahill [11] presented the findings of electrical short circuit and current overload tests performed on commercial aircraft wiring (ETFE or PTFE insulated). In this report, a series of currents were loaded to the wires to find out the ignition point. Thibert et al. [12] used the PITCAIRN oven and the EDF/CNRS Calorimeter to determine the evolution of net combustion heat of PVC cables. Babrauskas [5, 13] studied the factors leading to the ignition of low-voltage, PVC-insulated electrotechnical products to find out the related mechanisms and modes. The ignition temperature of commercial, flexible PVC formulations reported by several authors spanned the range from 513 to 695 K. Xie et al. [14] studied the fire protection properties of PVC sheath for old and new cables and found that the old cable would pyrolyze more strongly and completely than the new one. Although several studies worked on the wire fires, to the authors' best knowledge, few researchers have studied the effect of electric currents on the ignition of PVC insulated wires quantitatively.

The structure of smoke particles and their size distribution are important parameters for fire and smoke detection. The count median diameter (CMD) and the geometry mean diameter (GMD) are always used to describe the smoke particle size distribution. The morphology for fire smoke particles of standard test fires studied by several authors was fractal-like aggregate. These aggregates were composed of many primary particles, which had the size of 30-60 nm [15-17]. Moreover, the pyrolysis smoke particles could be considered as some spherical droplets that the volatile organic compounds were condensed into [18, 19]. Butler et al. [20] studied the generation and transport of smoke components to find out the information needed to assess the smoke aerosol exposure of an individual in a fire. Xie et al. [21] studied the time-dependent size distributions of smoke particles of standard test fires, and found that the normalized number distributions of smoke aerosol could be best fitted with lognormal functions.

From the perspective of fire detection, this paper aims to study the effects of current on the ignition time of externally heated PVC-insulated wires, as well as on the fire and pyrolysis smoke particles. Firstly, experiments on the ignition of energized wires under external heat radiation are performed with three kinds of wires to study the ignition time of externally heated wires with electric currents. Then pyrolysis smoke particles generated by the self-heated wires are also studied without external heat radiation. The results of this study may be useful for the electrical design and fire smoke detection for more widely use of electrical wires.

**EXPERIMENTAL SETUP**

The experimental apparatus used in this study is shown in Fig. 1, which is mainly composed of a combustion chamber, a fast particulate spectrometer (FPS), a sample holder, two constant current sources (CCS) and an ignition part. The inside dimensions of the chamber is 430 mm \((L) \times 210 \text{ mm} (W) \times 270 \text{ mm} (H)\). It is mainly used to stabilize air stream and reduce the influence on smoke collection.

The sample probe is placed above the center of the chamber to collect the smoke particles. It is connected to the FPS through the sample pipe. The FPS used here is DMS500 Mk II of Combustion Company. It could provide a size spectrum for particles between 5 nm and 1000 nm, and allow a response time of 200 ms. So, it could be used to realize the real-time collection and analysis of smoke particles generated by combustion of PVC insulation in different conditions.
The coil heater is used as an ignition source, which is made of nickel-chromium wire. The diameter of the coil is 0.5 mm, and it is wrapped around the wire with 20 mm length. In order to provide various external heat flux, the current imposed on the coil heater is precisely controlled by the CCS 2 with a measuring range 0-7 A and an accuracy ±0.01 A. The ignition part is removable, which is placed in the center of the wire sample to initiate ignition or removed to implement smoke collection experiments.

PVC insulation of electrical cables used in low-voltage applications typically comes in thicknesses of 0.4-1.2 mm [5]. Here, three types of PVC coated copper (Cu) and nickel-chrome (NiCr) wires are adopted in this study, which is shown in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Conductor metal</th>
<th>Conductor diameter ((d_c\text{ (mm)}))</th>
<th>Thickness of insulation ((\delta_p\text{ (mm)}))</th>
<th>Outside diameter ((d_o\text{ (mm)}))</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>Cu</td>
<td>0.50</td>
<td>0.25</td>
<td>1.00</td>
</tr>
<tr>
<td>B</td>
<td>Cu</td>
<td>0.60</td>
<td>0.40</td>
<td>1.40</td>
</tr>
<tr>
<td>C</td>
<td>NiCr</td>
<td>0.60</td>
<td>0.40</td>
<td>1.40</td>
</tr>
</tbody>
</table>

During the experiments, a front-view video camera (SONY NEX-5R, 50 fps) is used to record the ignition process. A compression spring is used to keep the sample wire tense and straight during the whole process. The CCS 1, which has a measuring range 0-21 A and an accuracy ±0.1 A, is used to change the electric current of the sample wire. All experiments are performed in a standard fire room.
Part II  Fire

with quiescent air. Generally, at least 5 repeated tests are conducted under the same condition in order to reduce errors.

RESULTS AND DISCUSSION

Ignition of wires

A typical ignition process is shown in Fig. 2. Once the coil heater is turned on, it could reach a high temperature quickly while the sample wire is heated and the PVC insulation begins to pyrolyze. During this process, the temperature of the insulation could be considered the same as that of the conductor for its much smaller thermal conductivity and thermal inertia. Then, a blue premixed flame develops, denoted as the ignition point (Fig. 2(a)). Afterwards, the inner face of the insulation also pyrolyzes to generate plenty of gases. Since the melting temperature of PVC is higher than the pyrolysis temperature [22], the gases between the core and the insulation would accumulate to some extent. When the gases breaks through the insulation, a jet flame, which is always near the center of the coil heater, comes out (Fig. 2(b)). Later, several jet flames appears with different flame height in every direction (Fig. 2(c)). However, the flame could not spread along the wire. At last, it comes to an extinction and leaves behind a char layer a little longer than the coil heater (Fig. 2(d)).

![Images of the ignition process](image)

**Figure 2.** The typical ignition process of Type B with the electric current of wire, $I_w = 0$ A and the electric current of the coil heater, $I_{ch} = 5.9$ A. (a) Ignition point; (b) jet flame point; (c) combustion process; (d) extinction

Fig. 3(a) shows the ignition time of wires, Type A and B, with $I_w = 0$ A as the external heat flux changes. The experimental results are shown with error bars. It is obvious that the ignition time concavely decreases with the increasing external heat flux for one certain type of wire. Besides, a larger conductor diameter and thicker insulation would increase the ignition time. In particular, in the experiments, the ignition time of Type A is much higher than that of Type B and has a big error bar when the current of coil heater is about 5.1 A. In this condition, the lower temperature gradient of wire leads to less pyrolysis gases in the heating zone, which would dissipate before the coil heater becomes hot enough as a pilot-ignition source. Therefore, a remarkably large ignition time appears. Fig. 3(b) shows the ignition time with different currents of wires while the external heat flux stays the same. The ignition time convexly decreases with the increasing current of wires for one certain type of wire. Besides, a larger conductor diameter and thicker insulation would increase the ignition time. When the current of Type A and Type B is beyond 14 A and 16 A respectively, the heat from the wire conductor drives the PVC insulation to pyrolysis and release a little white smoke.
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Figure 3. (a) Ignition time of wires with $I_w = 0$ A and different current of coil heater. (b) Ignition time with different current of wire and $I_{ch} = 5.5$ A.

**Smoke particles**

As seen before, it needs a huge current to make the PVC insulation pyrolyze for wires with copper conductor. For the limitation of CCS 1, wires of NiCr conductor, namely Type C, are adopted in the experiments of this part. Copper grids with lacy carbon films are used to collect smoke particles in order to study their morphology with Transmission Electron Microscope (TEM) and Scanning Electron Microscope (SEM). Besides, the FPS mentioned before is used to get the size distribution and change regularity of smoke particles.

Fig. 4 shows the characteristics of fire smoke particles. Type C wires are heated by the coil heater to catch fire, then the copper grids are placed right over the fire to collect the black smoke particles. The SEM image shows that these particles are fractal-like aggregates. The size of these aggregates varies from dozens of nanometers to a few microns. In the TEM image, it shows that fractal-like aggregates are composed of many primary particles, which have the size of 50-80 nm. These results are basically identical with the research about standard test fires.

Figure 4. Characteristics of fire smoke particles. (a) SEM image; (b) TEM image.
Without the external heater, a large current in the wires, which is more than 3 A in this part, would drive the PVC insulation to pyrolysis. However, when the current goes beyond 9 A, the Type C wires would fuse and a fire would come out. Therefore, to study the properties of the pyrolysis smoke particles, the current in the wire varies from 3 A to 9 A. During the pyrolysis process, plenty of white smoke appears. A cross-linked, charred residue remains at the end. Fig. 5 shows typical characteristics of pyrolysis smoke particles with Iw=8 A. From the SEM image, it shows that the particles are almost sphere with size about 100 nm. In the TEM image, the particles seem like spherical droplets with size over 160 nm. This is mainly due to the impact of the electron beam for analysis.

![Figure 5. Characteristics of pyrolysis smoke particles with Iw=8 A. (a) SEM image; (b) TEM image.](image)

For the purpose of early fire smoke detection, the data collected in the first 35 s after the wires energized is selected. As seen in Fig. 6(a), the smoke particle number concentration (SPNC) increases with the increasing current of wire. The change of the SPNC versus the current of wire could be divided into two regimes: (I) sudden increase with current addition (3-5 A); (II) mild increase with current addition (6-9 A). Fig. 6(b) shows the CMD and GMD of the smoke particles with different current of wire. Apparently, both the CMD and GMD decreases with the increasing current of wire. The behavior of the smoke particle size versus the current of wire could be divided into two regimes as well: (I) sudden decrease with current addition (3-5 A), CMD < GMD; (II) mild decrease with current addition (6-9 A), CMD > GMD. This two-regime phenomenon is probably due to the two degradation stages in the pyrolysis process of PVC [23-26]. The first stage happens at the temperature of 500-600 K. In this stage, plenty of hydrogen chloride (HCl), polyene hydrocarbon and a little alkylbenzene are generated. The second stage takes place at the temperature of 700-800 K, in which isomerization, crosslinking and aromatization of the hydrocarbon mainly proceed. So, in the first regime with a smaller heating rate, the PVC insulation mainly performs the first-stage pyrolysis while in the second regime with a higher heating rate, the second-stage pyrolysis dominates and generates hotter and denser smoke. Although the higher temperature and larger concentration of the smoke would enhance the Brownian coagulations to make the size of the smoke particles increase [27], the difference between the products generated in the two stages makes the smoke particles present the characteristics as Fig. 6(b) shows.
The behaviors of pyrolysis smoke particles with different currents of wire are found to be similar. Hence, electrical wire with the current of 5 A is chosen as a typical object to study. Fig. 7 shows the smoke particle size distribution with $I_w=5$ A at 35 s after the wire energized. The smoke particle size distribution could be well fitted with a lognormal distribution of GMD and geometric standard deviation being 209.9 nm and 2.0 respectively. The real data curve has two peaks at 24 nm and 137 nm respectively. This distribution seems similar to the smoke particles size distribution of the standard test fires [28, 29].
Accordingly, $SPNC$ first increases sharply, then increases a little slowly until 70 s and finally shows a fluctuant decrease. This decrease mainly caused by the coagulation and condensation of the smoke particles. As shown in this figure, smoke particles could be regarded to be generated mainly in the prior 70 s.

Figure 8. $CMD$, $GMD$ and $SPNC$ of smoke particles versus time with $I_w=5$ A after the wire energized.

CONCLUSIONS

Ignition of energized PVC-insulated copper wires by external heating was examined experimentally. The experimental results show that the ignition time concavely decreases with the increasing external heat flux while convexly decreasing with the increasing current of wire. PVC-insulated NiCr conductor wires were adopted to study the properties of fire and pyrolysis smoke particles. The morphology of fire smoke particles shows a fractal-like structure composed of 50-80 nm primary particles and independence to current of wire. The $CMD$, $GMD$ and $SPNC$ of pyrolysis smoke particles show a two-regime behavior with the increasing current of wire. The pyrolysis smoke particle size distribution with one certain current could be well fitted by a lognormal distribution, similar to that of the standard test fires. The time-dependent $CMD$ and $GMD$ with one certain current first increase, then decrease and finally fluctuate in the range of 90 nm to 120 nm. The results of this study may be useful in a fire hazard analysis or smoke detection modification of electrical wires and cables. Future work should be focused on investigating the light scattering characteristics of the smoke particles and modifying the smoke detectors to detect PVC-insulated wire fires.

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