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Research Article

Study on Flame Spread Characteristics of Flame-Retardant Cables in Mine

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Polymer combustion is an important factor in mine fires. Based on the actual environment in a mine tunnel, a cable combustion experiment platform was established to study the regularities of the cable fire spread speed and smoke temperature under different conditions, including various fire loads and ventilation speeds. The flame change and molten dripping behaviour during the fire spread process were also analyzed. The experimental results show that the flame-retardant cable can be ignited and continuously burnt at a certain wind speed, but the combustion can be restrained at high wind speed. The combustion speed of the flame-retardant cable is affected by the fire load and ventilation speed. The combustion droplets can change the shape of the flame, which can consequently ignite other combustible materials. The analysis of the experimental results provides an important basis for the prevention of tunnel fires.

1. Introduction

In recent years, polymer materials, such as cables and belts, have been widely used in mines [1]. As the main carrier of electric energy and information transmission, the cables are widely distributed in the mine. The cables are made up of conductors, insulators, fillers, wraps, and sheaths, and the most common materials for the cable sheath in China are chloroprene rubber (CR), polyvinyl chloride (PVC), polyethylene (PE), and chlorinated polyethylene (CPE), etc. While the cable has the problems of overload, short circuit, and other faults, it may cause fire and explosion accidents and the use of polymer materials increases the fire risk of the workplace [2]. With the special mine environment, the tunnel belongs to the semienclosed space, the structure of which is very complicated [3], and the cables are arranged in every tunnel. Once the cables catch fire in the tunnel, the poisonous and harmful gases from the burning cables will flow across the downstream area, threatening the miner's life safety [4, 5]. For the reasons mentioned above, the "coal

mine safety regulations" promulgated by China stipulates that "fire-retardant cables for safety signs of coal mine products must be selected underground." However, fire-retardant cables are not noncombustible, which can be burnt under certain circumstances [6]. For example, ten miners died in the fire-retardant cable fire which happened in the Chengcheng Sulfur Mine of Shanxi Province.

At present, domestic and international scholars studying cable polymers in tunnels are mainly divided into two parts. Some established the cable combustion experiment platform according to the actual environment of the tunnel, and the char length of cables covered with coating was investigated under different fire loads and ventilation conditions. Li [7] established a cable fire model in various environments to analyze the spread of cable fires. Carcillo [8] studied the fire behaviour of electrical cables in the cone calorimeter and the influence of cables' structure and layout. Xu [6] studied the combustion and flame-retardant characteristics of PVC-sheathed cables. Liang [9] focused on cable fire spread and smoke temperature distribution in a T-shaped utility tunnel.

Rickard [10] analyzed the fire behaviour involving multiple fires in a mine drift with longitudinal ventilation. The other scholars used FDS software to simulate the occurrence of cable fires, analyzing the changes of temperature field [11], smoke flow field [12, 13], and temperature with the changes of the fire source power in different types of tunnels [14–17]. However, few scholars are committed to cable fire spread and much less attention is paid to the fire load, impact of ventilation speed on flame shape, influence of fire spread speed in a cable fire, and melting and dripping produced by the polymer as the combustible is heated.

In this paper, the role of the cable layout and air ventilation on the fire behaviour of a series of flame-retardant cable which was used in the mine of China was thoroughly investigated. The study involves the flame spread processes of one and two arrangement of cables under different wind speed conditions.

2. Experiment Design

The tunnel model (see Figure 1), which opens at both ends, has dimensions of $3\,\text{m} \times 0.26\,\text{m} \times 0.26\,\text{m}$ (length × width × height). The interior of the box is made of asbestos boards with certain thermal insulation, and fireproof glass is installed on the side as the observation window. A cable bridge with a length of 3 m and a width of 0.2 m is placed in the tunnel divided into two layers, and the lower layer and the upper layer are at heights of 0.03 and 0.13 m from the bottom, respectively.

A layer of thermocouples is arranged along the central line of the tunnel to measure the temperature. The upper five thermocouples A1–A5, 0.15 m high from the bottom, are 1, 1.25, 1.5, 1.75, and 2 m away from the air inlet, respectively. The probe is located right above the cable, and the data acquisition frequency of thermocouples is 5 s each time.

Cable fires in the tunnel are mainly caused by external ignition or short circuits, both of which occur in the presence of a stable heat source. In this study, the experimental fire source is the burning pine and the fuel is diesel oil. The ignition source is located 1 m away from the air inlet to allow observation of the combustion process of the cable.

The mass loss in the fire spread process is measured by an electronic balance with a measurement range of 2000 g and an accuracy of 0.01 g (WT C20002 series). The mass loss rate is obtained by further data processing.

In the experiment, to improve ventilation, an axial fan (SFG 3-2) is connected with a ventilation pipe with a length of 1 m. In addition, high-speed photography (Sony ILCE-5100L APS-C) is set 1 m in front of the tunnel model,which is used to record the flame spread speed, flame height, and flame spread trace of cable combustion in the tunnel.

According to the national standard JB/T8735.2-2016, the experimental materials (see Figure 2) are flame-retardant cables (type3 × 2.5) with a diameter of 11 mm, whose sheath is ethylene propylene diene rubber-insulated. Single and double cables with lengths 1 m are selected and built in the bridge frame. Once the cable is ignited, the fire source will be removed. By changing the fire load and wind speed, the combustion speed and the temperature at each measuring point, as well as flame spread trace, are measured to obtain the variation of the cable fire. The results are used to guide the fire prevention design of the tunnel cable.

3. Results and Discussion

3.1. Heat Release Rate Analysis of the Cable. The heat release rate of the solid combustible, an important parameter to measure the fire hazard, is the heat released by the combustion material in unit time. In the present study, 100 g sample cables were burned on an electronic balance. The size of the confined space is $175\,\text{mm} \times 150\,\text{mm} \times 90\,\text{mm}$. Both sides of this space are ventilated with the flow rate of air $2\,\text{m}^3/\text{min}$. The pump is installed in the pipeline, and fresh air is added from the environment at the bottom of the experiment room. The cable sample is ignited, and the external heat flux is $25\,\text{KW/m}^2$. When the cable catches fire, remove the external heat flux. The dynamic data of cable mass are recorded by an electronic balance at 5 s intervals, thus the mass loss rate can be obtained. Finally, the cable heat release rate is calculated by the following equation:

$$Q = \alpha m q, \tag{1}$$

where Q is the heat release rate, kW; α is the combustion efficiency factor of the combustible ($\alpha = 1$ for complete combustion; α usually ranges from 0.3 to 0.9); m is the mass loss rate of the combustible, kg/s; and q is the average calorific value of the combustible, kJ/kg. The combustion heat value of rubber is $35 \times 10^3\,\text{kJ/kg}$.

Figure 3 shows that the heat release rate of the rubber cable sample with a airflow rate of $2\,\text{m}^3/\text{min}$. When the temperature reaches a certain level, the top layer of rubber begins to crack, producing volatile gas which is ignited to a certain concentration. Then, the heat release rate increased sharply in a short time and reached its peak value as pyrolysis combustible gas increases. With the supply of air, the cable sheath is in contact with oxygen constantly and the heat release rate enters a steady stage, making the combustion continue.

3.2. Gas Temperature Changes in the Combustion Progress. The fire gas temperature refers to the airflow temperature measured in the middle of the section as the representative temperature in the tunnel. A1–A5 temperature curves are, respectively, represented by different colour curves. Figures 4 and 5 show that the oxygen supply for the combustion in the tunnel is more sufficient with an 11 Hz fan. The temperature in the developing stage is relatively stable, while the inflection point in the attenuation stage is also obvious.

The fire gas temperatures of A1–A5 (see Figure 5) with the double cable are higher than their corresponding values with the single cable (see Figure 4). The maximum fire gas temperatures of the single cable and double cable are 170°C–180°C and 400°C–500°C, respectively.

3.3. Flame Spread Speed. Figure 6 presents the variation curves of cable flame speed under different fire loads with a
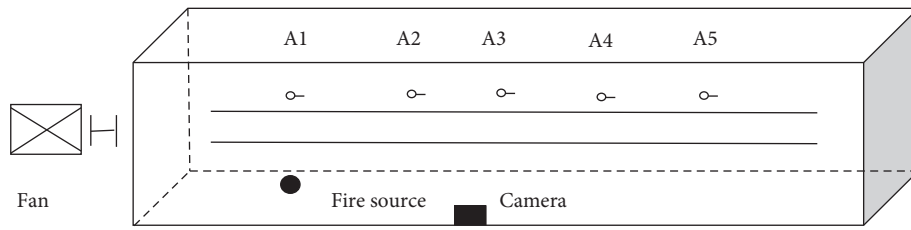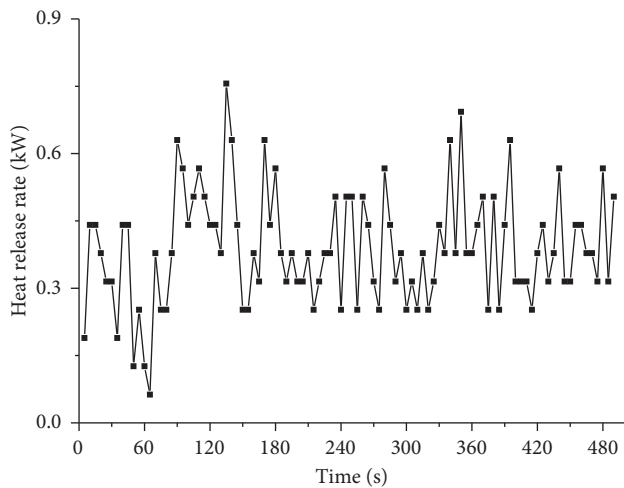
Figure 1: Tunnel platform.

Figure 2: The image of the cable sample.

Figure 3: Heat release rate of the rubber cable sample with an airflow rate of $2\,m^3/min$.
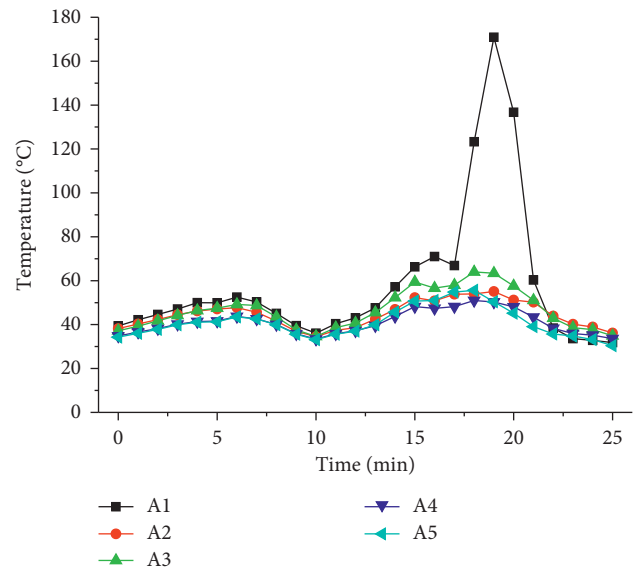

Figure 4: Temperature curves in the tunnel with a single cable with a fan frequency of 11 Hz.
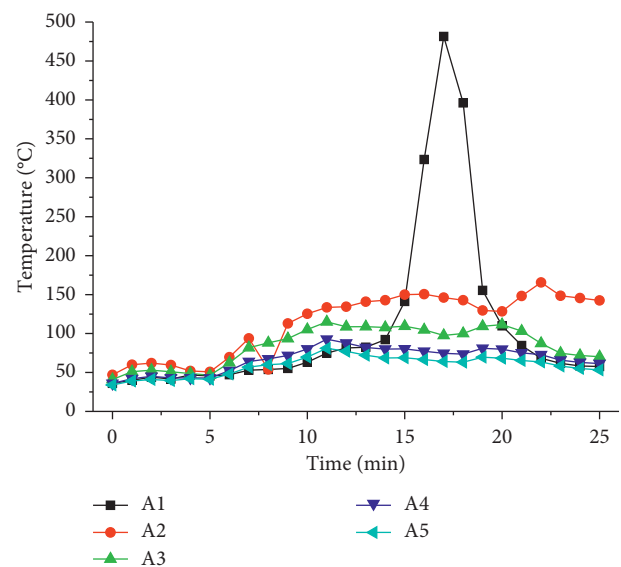
Figure 5: Temperature curves in the tunnel with a double cable with a fan frequency of 11 Hz.

fan frequency of 11 Hz. According to the test results, the flame speed of the cable increases with the fire load. This is because, in a confined space, heat released by a large number of cables is easy to gather and the cross-radiation among cables is obvious and can preheat the unburned cables and facilitate their combustion.

Moreover, as the combustion spreads continuously, the flame speed decreases and an inflection point appears, indicating that the flame in the binding joint or the lap joint will also affect the flame combustion speed.
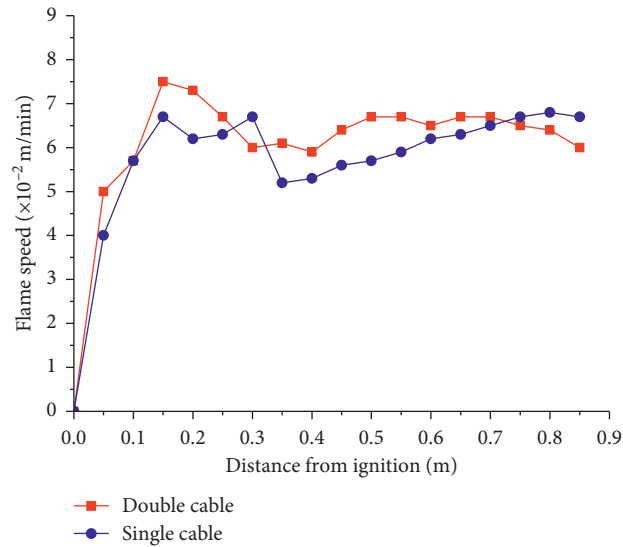
FIGURE 6: Flame spread curve of different cable with a fan frequency of 11 Hz.

When the fan frequency increases to 15 Hz, the combustion spread length keeps decreasing until the fire is extinguished, demonstrating that excessively high wind speed inhibits combustion. This is mainly due to the airflow cooling effect which can produce disturbance to the cable flame. As a result, the obtained heat of the unburned area decreases and the flame speed slows down. The cable fire spread length also decreases accordingly.

3.4. Characteristic Analysis of Flame Spread. In the experiment, the flame spread processes of single cable and double cable are recorded by high-speed camera. Through observing, it can be found that the combustion begins when the thermal contact temperature from the ignition source is within the ignition limit and the temperature is higher than the ignition point. Figure 7 presents the flame spread images of the cable combustion under no wind conditions. The flame shape varies with time: it changes from single-peak fire to double-peak, then to triple-peak, while the length of flame spread keeps increasing.

With increasing smoke in the tunnel, the contact between the cable and oxygen is disturbed. One hundred and forty three seconds after the combustion starts, it enters the decaying stage and will be extinguished at 202 s. It can be concluded that the rubber cable keeps burning due to the thermal decomposition of the heated combustible. As long as the heat supply to the cable is sufficient to sustain the rate of polymer degradation required by the flame, the combustion will continue, otherwise, the flame will die out.

Figure 8 presents the flame spread images of the single cable combustion with the fan frequency of 11 Hz. The flame burns along the wind direction at this fan frequency. At 129 s, part of the heat energy generated by the gas flame flows to the unburned area, causing thermal decomposition of the polymer. The combustible gas produced by the thermal decomposition then combines with oxygen in the air, which promotes the combustion flame spread without interruption.

At 311 s, the flame is affected by the temperature and pressure gradient in the tunnel as well as the throttle effect on the downwind side of the fire source. Fresh air flows to the fire source on the bottom of the tunnel along the wind direction, while the smoke flow generated by the fire source flows reversely on the ceiling of the tunnel on the upwind side and rolls back to the fire source. The backflow smoke can make the combustibles on the windward side catch fire. Meanwhile, the rolling smoke flow in the tunnel may induce a gas explosion when it mixes with fresh air on the windward side of the fire source and flows back to the fire source again.

The molten appears at 1244 s. As the burning molten gradually detaches from the wire, the cable flame jumps wildly. The droplet separated from the cable appears to be burnt as it falls off from the cable. At this dropping moment, the flame above the cable becomes thinner and longer and the flame volume decreases obviously [18–20].

Figure 9 shows the flame spread images of the double cable combustion with the fan frequency of 11 Hz. At 64 s, the fire enters the developing stage. The heat generated by the double cable accumulates so that the flame height and fire spread speed are significantly faster than those in the scenario with the single cable.

The temperature of the heated cable increases drastically at 449 s. Since the temperature is higher than the melting temperature or viscous flow temperature, the cable will be gradually softened until the molten flows at 452 s. This is due to the breakdown of the thermoplastic polymer which makes
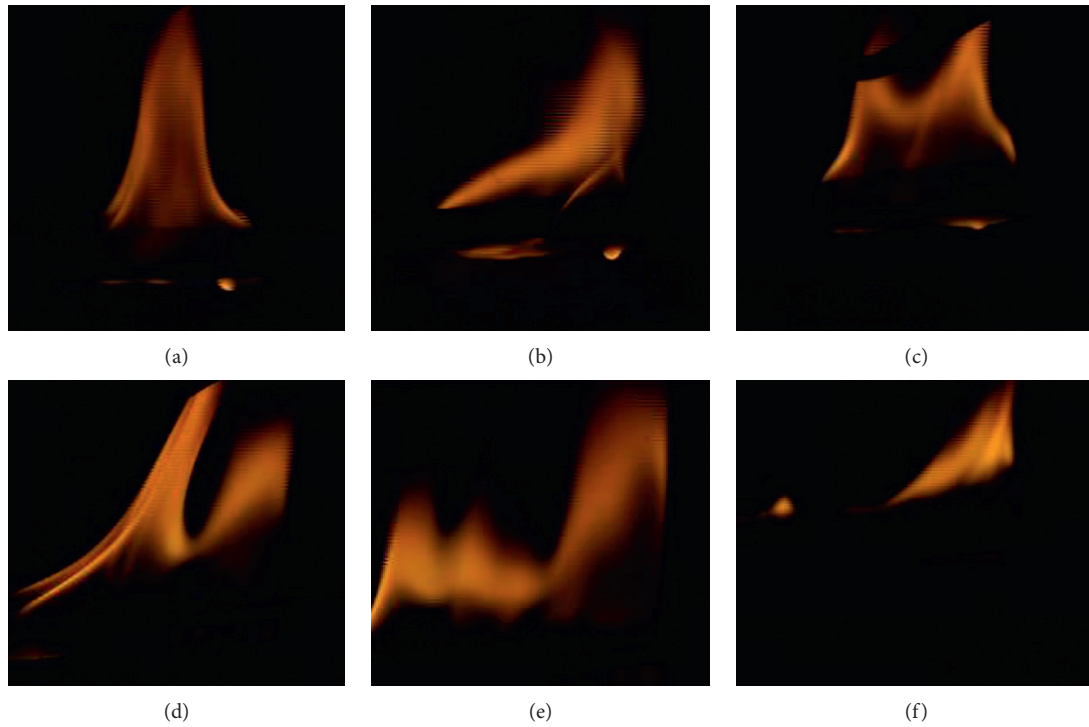
FIGURE 7: Images of flame spread under calm condition. (a) $t = 4$ s, (b) $t = 8$ s, (c) $t = 18$ s, (d) $t = 43$ s, (e) $t = 67$ s, and (f) $t = 143$ s.
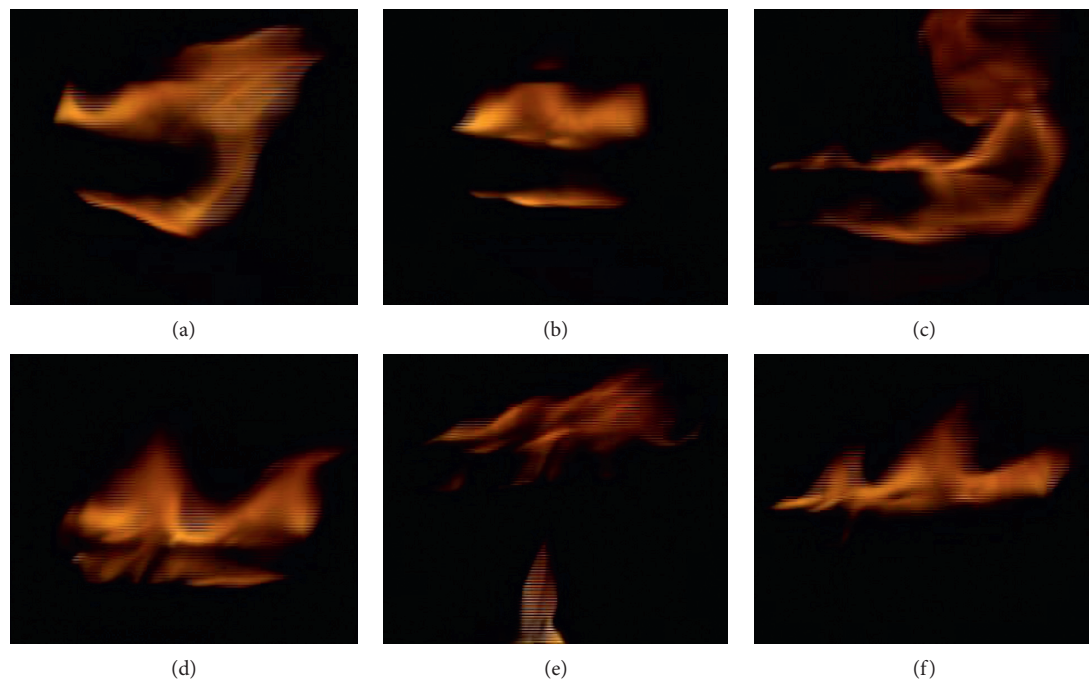

FIGURE 8: Images of a single cable flame spread at a fan frequency of 11 Hz. (a) $t = 129$ s, (b) $t = 131$ s, (c) $t = 311$ s, (d) $t = 1205$ s, (e) $t = 1244$ s, and (f) $t = 1277$ s.

its molecular weight and viscosity decrease. Therefore, more and more molten drops or melt were produced. The droplet has a higher temperature after a long-distance drop, which can ignite other combustibles. The scope of the fire may expand if it is not dealt with, causing the rapid development of fire and serious consequences.
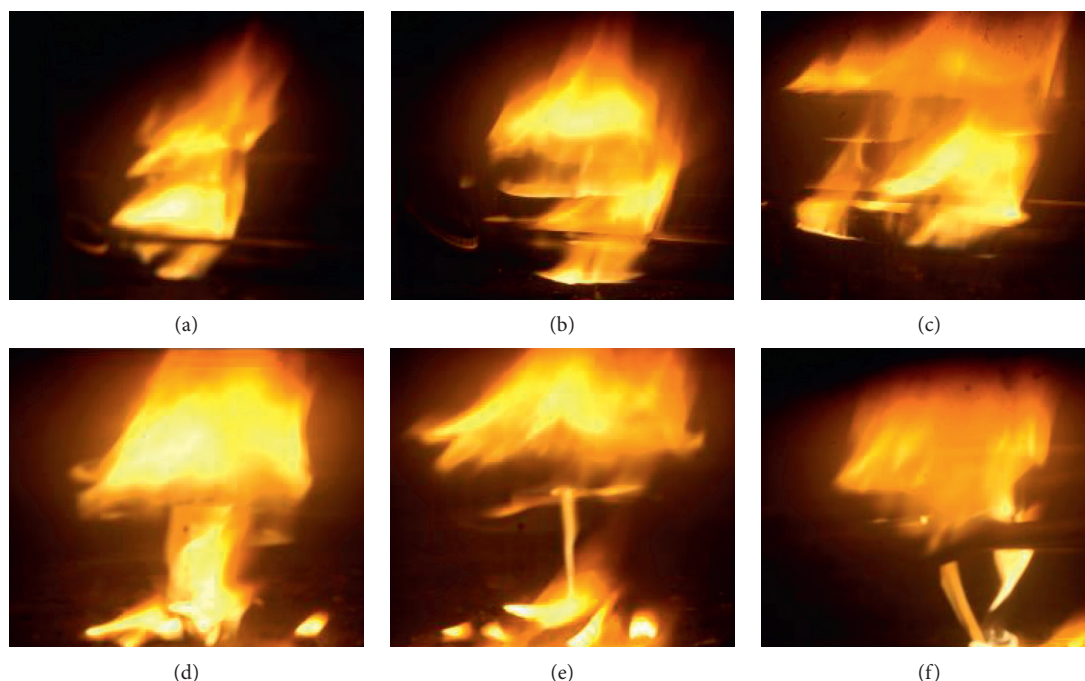
FIGURE 9: Images of double cable flame spread at a fan frequency of 11 Hz. (a) $t = 64$ s, (b) $t = 111$ s, (c) $t = 175$ s, (d) $t = 449$ s, (e) $t = 452$ s, and (f) $t = 744$ s.

4. Conclusion

(1) The heated flame-retardant cable can be decomposed and catch fire. Under certain wind speed conditions, partial heat generated by the flame gas flows to the unburned areas so that the polymer in these areas will be decomposed and start burning. The wind speed keeps increasing and suppresses the combustion until the fire is extinguished. As a result, the wind speed can affect the cable fire spread.

(2) In the combustion process, the cable exhibits molten flow phenomena, producing a large amount of molten with the change in the flame shape. The melting drops with a higher temperature after the long-distance travel can ignite other combustibles.

(3) The flame is affected by the temperature and pressure gradient in the tunnel as well as the throttle effect on the downwind side of the fire source. The backflow smoke phenomenon is produced. Meanwhile, the smoke flow rolling back in the tunnel mixes with fresh air on the upwind side of the fire source and flows back to the fire source again, which may induce a gas explosion.

Data Availability

The figure data in this paper used to support the findings of this study may be released upon application to the College of Safety Science and Engineering of Liaoning Technical University, who can be contacted with the corresponding author Gao Ke, and the E-mail is gaoke@lntu.edu.cn.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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