Smoke Emission and Distribution Characteristics of Overloaded Wire Insulations under Microgravity

Hanhan Zhuang · Wenjun Kong

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Abstract
With the development of manned space technology, spacecraft safety and fire prevention have attracted more and more attention. Due to the disappearance of buoyancy in microgravity, the fire early monitoring, detection and alarm technologies designed based on the ground experimental results are not suitable for spacecraft. It is necessary to develop fire early monitoring technology in microgravity. Smoke is an important early monitoring signal for fire prevention both in normal gravity and microgravity. Under microgravity, fire is mostly caused by overload or aging of wire insulations. In order to study the smoke emission characteristics of wire insulations under microgravity, we carried out the overload experiments of wire insulations on board the SJ-10 Chinese recoverable satellite. The smoke generation characteristics captured by laser extinction methods, and a large number of experimental data in the real microgravity environment were obtained for the first time. In this paper, the smoke volume fraction in the early and axisymmetric stages of smoke emission from the wire insulating layer are obtained by using the method of Abel transform and convolution, and the MATLAB algorithm program is compiled. In the later stage of smoke emission, it does not show axisymmetric distribution, but the laser extinction results can be used for obtaining the smoke emission trajectory. According to the results, edge jet smoke emission modes in the early stage of ignition of wire insulation in microgravity are quantitatively analyzed. The effects of insulation thickness, overload current and insulation material on smoke emission are discussed.

Keywords Fire safety · Microgravity · Laser extinction · Wire insulation · Overload · Smoke emission and distribution

Introduction

The growth of manned spaceflight puts forward higher requirements for safety and stability in space. Fire safety is one of the most important problems that must be properly solved and is directly related to the safety of astronauts and the success or failure of the overall mission. In the history of human space exploration, there have been many fire events (Thompson et al. 1967; Cortright 1970). According to NASA statistics, at least five fires occurred in the first 50 flights of the space shuttle. Most of these accidents were caused by the failure of electronic and electrical components, such as wires. However, the alarm system in the spacecraft could not recognize and send out early warning signals, but abnormal smells or smoke from the fire site was detected by astronauts who subsequently found the fire (Friedman 1994). Wires are typical electrical and electronic components. Wire fault, such as aging and overload, is an important fire potential hazard in manned spaceflight.

Studies on the ignition characteristics of wire insulation in microgravity have been conducted for approximately 50 years. Thomas et al. (1971) experimentally studied the ignition characteristics of Teflon-insulated nickel core wire with external heat source ignition on the drop tower, confirmed the characteristics of sustainable combustion of Teflon insulation in microgravity environment, and found that the flame spread speed will be relatively reduced in microgravity environment. Paxton et al. (1993) experimentally investigated the combustion behavior of overheated wire samples for normal and microgravity conditions. The wire insulation heated by the hot wire with pulse energization. The microgravity tests conducted in the 2.2 s drop tower at NASA. Three wire insulation materials representative of spacecraft application were used in the experiments, two were found to flame in microgravity but not in normal
gravity. The third insulation did not flame, but there was more thermal degradation of the insulation at microgravity. Thus, the wire insulation is more likely to cause fire in microgravity. The results are useful for the selection of spacecraft wire insulation (Paulos and Apostolakis 1998). Greenberg et al. (1994, 1995) studied the flame spread characteristics of preheated polyethylene insulation in the glove box of the space shuttle. The ignition of polyethylene insulation layer was realized by first energizing and preheating, and then using winding resistance wire as external ignition source from one end side. It was found that in quiescent environment, the cracking of insulating layer in microgravity environment produced gas reaction products wrapped in wires, which was difficult to create sustainable visible flame. In the forced convection atmosphere, the phenomenon of bubble nucleation was observed in the melted insulating layer. At the same time, it was found that the flame spread rate on the surface of the insulating layer was closely related to the inlet flow direction and atmosphere. Japanese researchers (Kikuchi et al. 1998; Fujita et al. 2000, 2002) used the above similar method to carry out the wire insulation experiments on a drop tower. In the experiments, the effects of oxygen concentration, initial wire temperature, wire diameter, pressure, dilution gas and opposed external flow velocities on the combustion characteristics of the wire insulation were examined with emphasis on the flame spread rates. In addition, parametric studies were carried out on the effects of core on flame spread characteristics over wires for various inclination angle, ambient air flow, oxygen concentration and so on (Nakamura et al. 2009; Hu et al. 2015, 2017a, b; Lu et al. 2019; Jia et al. 2022). The study results of Huang et al. (2013, 2020) showed that the wire core with high thermal conductivity is easy to lead to ignition failure and extinguishment of weak flame. Korean researchers (Lim et al. 2017; Kang et al. 2021, 2022) studied the effects of electric field frequency and voltage on ignition failure and extinguishment of weak flame. Korean wire core with high thermal conductivity is easy to lead to ignition. The results showed that the microgravity environment significantly increases the ignition probability, including the occurrence of delayed ignition and extended ignition limits, with large electric currents when compared with the situation under normal earth based gravity. Shimizu et al. (2017) studied the ignition of electric wire after long-term excess current supply in parabolic flights. The results showed wire insulation was ignited by much lower electric currents under microgravity than under normal gravity and that the ignition delay time increased as the applied current decreased. It was further found that the total electric energy required for ignition increased with a decrease in the current value. Fang et al. (2018) studied the pilot ignition of the fluorinated ethylene propylene wire insulation in a sub-atmospheric pressure test chamber while applying constant high current, and they found that the bursting was more probable at the center of the wire. Previous experimental studies on smoke emission characteristics of wire insulation in drop tower showed that the smoke particles were spherical or ellipsoidal and are approximately twice as large as those produced in normal gravity, and the nature of the particle aggregates was dependent on the color of the insulation (Apostolakis et al. 1995; Srivastava et al. 1998).

However, the test time of the 2.2 s drop tower is too short, the smoke from the wire insulation layer doses not have enough time to generate under microgravity, and the trajectory of smoke in the confined space under microgravity cannot be obtained. Thus we suggested to investigate the smoke emission in the early stage of wire insulation by overload heating and the dispersion characteristics of the emitted smoke in the limited confined space on board SJ-10 satellite with long term microgravity (Hu et al. 2014, 2017a, b; Hu and Kang 2019). We have published some of these experimental results (Kong et al. 2016, 2019; Xue and Kong 2019), two smoke emission modes, namely the end smoke jet and the bubbling smoke jet, were identified with polyethylene and polyvinyl chloride insulations.

The purpose of this paper is to process the smoke emission images from experiments completed on board SJ-10 satellite to obtain the quantitative data of the early axisymmetric stage of smoke emission from the insulation by overload heating and the trajectory distribution of subsequent smoke emission.
Microgravity Experiments on Board the SJ-10 Satellite

The microgravity experiments were carried out on board the 24th recoverable satellite of China, the SJ-10 satellite, on April 6th 2016 launched at Jiuquan Satellite Launch Center (Hu et al. 2017a, b; Hu and Kang 2019). The microgravity level is better than $10^{-3} g_0 @ \leq 0.1$ Hz. The wire payload was in the orbit capsule. According to the ground screening experiment, we set up 7 working conditions. To reduce the influence of motor motion noise on satellite microgravity level, we set up a sample bin. All seven wires were installed in the same sample bin. There is no need to move the samples during the experiments, and the camera can capture the images of all samples during the experiments. Figure 1 shows the sample arrangement unit in the microgravity experiment, and Table 1 shows the parameters of the seven wires. The effects of different insulation thicknesses (0.2 mm, 0.4 mm, 0.5 mm), different insulation materials (polyethylene (PE), polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC)) and different overload currents (3.2 A, 3.9 A, 4.5 A) on the overload wire characteristics were studied. The core was Cr$_{50}$Ni$_{50}$ with a diameter of 0.5 mm, and the total resistance was 0.356 $\Omega$. The effective length of the insulation was 40 mm and that of the core was 70 mm. The distance between the two parallel wires was 15 mm. Thermocouples were located in the middle of each wire.

Laser extinction method is used to measure the smoke concentration volume fraction in the early axisymmetric stage of smoke emission by overload heating, and the subsequent laser extinction images can be used to obtain the trajectory distribution of smoke emission in the confined space. The laser light extinction measurement images were captured by CCD and a two-dimensional array of data is acquired simultaneously as used previously in microgravity (Greenberg and Ku 1997). The optical path arrangement in the measurement system is shown in Fig. 2. During the experiment, a beam of stable light was emitted by the laser transmitter, which entered the convex lens after turning through the mirror. Under the action of the convex lens, the light was collimated into parallel light and entered the experimental sample unit. Then, after the beam was acted on by the beam splitter, one path directly entered CCD camera 1 to obtain the real images without extinction, and the other path entered CCD camera 2, which was equipped with a narrow-band filter to obtain images after laser extinction. The light was stable during the experiment and the images were clear. An algorithm program was developed to process the image data.

Data Processing Method

The laser extinction method is an important method to measure the volume distribution of soot in flames. Its principle is shown in Fig. 3. When a laser beam passes through a flame region with soot particles, the laser intensity will be attenuated by the absorption and scattering of the soot particles. The extinction degree is related to the soot concentration. According to a certain algorithm, the soot concentration in the flame can be inverted by the images before and after extinction, as captured by the CCD camera.

There is a laser beam with an initial intensity $I_0$ and wavelength $\lambda$. According to the Lambert–Beer law, the attenuated laser intensity $I$ can be expressed as (Greenberg and Ku 1997)

$$dl = -K I_0 dx$$

(1)

In this study, the diameter of the soot particles is much smaller than the laser wavelength, and the particle is approximately spherical, which meets $\frac{\rho}{\lambda} < 0.3$. Therefore,
the scattering effect of soot on the laser can be ignored (Greenberg and Ku 1997; Konsur et al. 1999; Thomson et al. 2008). According to Rayleigh’s law, the relationship between soot concentration $f_v$ and extinction coefficient $K_e$ can be given as follows:

$$f_v = \frac{\lambda K_e}{6\pi E(m)}$$  \hspace{1cm} (2)

where $E(m)$ is the particle absorption term. The related literature considered that $m$ is constant in the visible and near-infrared range, i.e., the $E(m)$ function is constant (Smyth and Shaddix 1996). In the study of Iuliis et al. (1998), a fitting formula for the complex refractive index coefficient $m$ versus wavelength $\lambda$ was given. It was considered that for $300 \text{ nm} \leq \lambda \leq 800 \text{ nm}$ ($\lambda = 632.8 \text{ nm}$ in this study), this formula had a high accuracy.

For smoke with an axisymmetric distribution, inversion algorithms can be used to calculate $K_e$. Dasch (1992) compared the Abel Transform algorithm, the Onion Peeling algorithm and the Filtered Projection algorithm in detail, and the Abel Transform algorithm was considered to be the best. Its calculation process is relatively easy, and the accuracy of the three-point Abel Transform is higher than that of the two-point Abel Transform. Therefore, the three-point Abel Transform algorithm is used in this study.

For the images processing, it is necessary to denoise the obtained images to obtain more accurate calculation results. The image processing procedure can be described as follows:

1. Image averaging. The average filtering of multiple adjacent images can solve the problem of large signal noise in a single image.

2. Ratio images. The gray matrix of the experimental image is divided by the gray matrix of the background image to obtain the gray ratio matrix. On the one hand, fixed interference in the field of view is eliminated to a certain extent. On the other hand, the gray ratio of each pixel can reflect the absorption and scattering of the laser by solid particles in the experimental field, which is the core parameter of subsequent calculations.

3. Gauss denoising. When the Gaussian filtering threshold is input, the noise on the image is generally expressed as a high-frequency signal. The extinction of high-frequency noise can eliminate spatial clutter and make the calculation object clearer.

4. Boundary treatment. The boundary cutting threshold is input to address the flame boundary and its internal impurities to form a clear and meaningful boundary.

5. Midline positioning. The gray values of two adjacent points are differentiated to find the flame boundary. The centerline is determined by using the midpoint coordinates of the left and right boundaries, and the axis position of the equivalent axisymmetric flow field is calculated.
(6) Mirror average. Taking the median line as the axis of symmetry, a rotatable surface is formed numerically to describe the axisymmetric smoke distribution.

(7) Concentration calculation. A MATLAB program was used to calculate the volume fraction of the wire smoke concentration. After judging that the data are valid, they are imported into Tecplot to generate a smoke distribution cloud map for subsequent analysis.

Results and Discussions

According to the experimental results obtained from the SJ-10 payload, the temperature and smoke emission characteristics during wire overload were initial analyzed by Xue and Kong (2019). Two typical smoke emission modes in the early stage of ignition of wire insulation overload under microgravity were proposed as edge jet emission and bubble jet emission, and the smoke emission process and morphological evolution characteristics of the two modes were described. In this study, the smoke emission trajectory and concentration distribution characteristics of the edge jet mode are quantitatively analyzed from the calculation results of the laser extinction images. The smoke emission trajectory characteristics of the bubble jet mode are described in detail.

Smoke Emission and Concentration Characteristics of Edge Jet Mode under Microgravity

Figure 4 shows the smoke emission trajectory and volume concentration distribution of the edge emission mode with insulation of PE, insulation thickness of 0.5 mm and current of 3.2 A. According to the principle of axisymmetry, only one side is calculated. The dark red slender rectangular region represents the energized experimental wire, the white dotted lines represent the position of adjacent wires, and the gray rectangles at both ends represent two fixed copper ports. It can be observed that the smoke first emits from the wire’s two ends at 70 s. This is because under current’s heating action, the internal insulation near the wire core is first pyrolyzed. The insulation at both ends are exposed to the air and react with oxygen first, so both ends of the insulation become the outlet of smoke. Therefore, the smoke emission is detected at both ends. With the passage of overload time, the smoke concentration gradually increases, but the injection angle of the main jet at both ends remains basically unchanged. The above phenomenon is quite different from that observed under ground. To study the influence of low pressure environment on smoke emission, an experiment on smoke emission characteristics of overloaded wire insulation under normal gravity was carried out by Xia et al. (2016). As
shown in Fig. 5, in the normal gravity and ambient pressure environment, due to the buoyancy, the smoke trajectory diffused upward along the vertically placed wire can be seen. The smoke detection device installed on the top can monitor the smoke well in this case. In the normal gravity and 3 kPa pressure environment, with the weakening of buoyancy,
the smoke is gradually emission upward at a certain angle, which can be compared with the smoke emission mode at the upper end of the wire under microgravity. However, as the buoyancy still exists, the smoke at the lower end of the wire still spread upward, and there is no edge jet mode like that under this case. As shown in the experimental results in the real microgravity environment in Fig. 4, the convection basically disappears due to the buoyancy is greatly weakened. The smoke emits slowly in all directions in a symmetrical manner under the influence of diffusion. At this time, the smoke detection device installed on the top cannot capture the smoke signal in time. It can be seen that the real microgravity experiment differs greatly from the results of the functional simulation experiment in the ground. Therefore, the early smoke detection and alarm technology based on the ground experimental results is not suitable for microgravity environment.

In addition, quantitative analysis is made from the concentration distribution of smoke. As shown in Fig. 4, the stable smoke emission state was reached at about 110 s. Owing to the disappearance of natural convection in microgravity, the emitted smoke could only be transported away by diffusion, so it was very slow and the smoke could not be removed in time and accumulated at both ends of the wire. The newly generated smoke had a strong accumulation effect on the previous smoke, resulting in the formation of long ellipsoidal smoke clouds visible to the naked eye on both ends. Smoke with a high concentration of 10–15 ppm was accumulated in the main jet area in the middle of long ellipsoidal smoke clouds. Under the effect of slow diffusion, the concentration of smoke at the edge of the main jet was slightly lower than that in the middle, which was 2–10 ppm. When smoke was emitted to the copper port of adjacent wires, a high concentration of 15–60 ppm would be accumulated. This result indicates that when smoke encounters obstacles, diffusion is weakened and there is no natural convection, so it is more difficult to remove smoke, which makes it rapidly accumulate locally and form a high concentration smoke area. Carefully, the smoke at the upper and lower ends was not completely symmetrical, which can be explained from the ground experiment. Under normal gravity, the whole smoke moves upward due to buoyancy, and the greater the buoyancy, the smaller the angle between smoke jet and electrified wire. In Fig. 4, the main jet at the lower end of wires tended to move upward, and the jet angle at the upper end became smaller, which was a manifestation of a very small amount of residual buoyancy. This experiment was conducted in a microgravity level of about $10^{-4} g_0$, a small residual buoyancy existed. The very small buoyancy does not affect the overall smoke emission direction, but may cause a slightly uneven distribution of the insulation pyrolysis products during the subsequent process. Compared with the normal gravity environment, the small residual buoyancy can be completely ignored, and it does not have much impact on the overall smoke distribution. The results in Fig. 4 also show that the calculation process can eliminate the stray dots in images, and the whole process of smoke emission can be observed more visually and effectively by excluding other disturbances in the field of view compared with images obtained directly from the experiment.

**Smoke Emission Trajectory Characteristics of Bubble Jet Mode under Microgravity**

Figure 6 illustrates the smoke emission trajectory in bubbling injection mode with insulation of PVC, insulation thickness of 0.4 mm and current of 3.2 A. As time went on, bubbles appeared from the outer surface of wire insulation layer and gradually broke, a large amount of smoke was ejected. The emitted smoke was asymmetric, and we mainly analyzed the trajectory distribution of smoke emission. A hemispherical bubble could be seen at the early stage of the bubble jet mode. This is because the insulation is melt and pyrolyzed first on the side near the inside of the wire core, and the tension on the outer surface of the insulation allows pyrolysis products to accumulate inside. As the reaction proceeds, the outer surface of insulation layer cannot provide greater tension to maintain the bubble, resulting in the bubble rupture and the release of the accumulated pyrolysis products. Figure 6 demonstrates that a large amount of smoke sweeping over the adjacent wire area after the bubble ruptures. However, higher energy is required for the anaerobic pyrolysis reaction. Thus the insulation layer receives more heat from the wire core during reaction and the temperature of products ejected from

![](image-url)

**Fig. 8** Variation of smoke concentration with time for wires with different insulation thicknesses

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the bubble increases accordingly. When the smoke sweeps over the adjacent area, especially when encountering obstacles, the accumulation effect of smoke described in the previous section will have a high temperature heating effect on them. Consequently, it can be seen that the bubble jet mode will affect the electrical and electronic components in the vicinity of overloaded wires, which is a space fire factor that cannot be ignored.

Effect of Insulation Thickness on Smoke Emission Trajectory Characteristics under Microgravity

Wires #1, #2 and #3 in Table 1 were selected to study the influence of the insulation thickness on the smoke distribution of overloaded wires. The insulation of these three wires corresponds to thicknesses of 0.2 mm, 0.4 mm and 0.5 mm respectively, and the insulation material is PE with

**Fig. 9** Smoke emission trajectory of wires with different currents. 
(a) wire#2: 0.4 mm, PE, 3.2 A. (b) wire#4: 0.4 mm, PE, 3.9 A. (c) wire#5: 0.4 mm, PE, 4.5 A
current of 3.2 A. The calculated result is shown in Fig. 7. The smoke signal was detected on the laser extinction camera of wire #1 after approximately 35 s, but no obvious symmetrical edge injection mode was observed at this time. It appeared directly the emission trajectory of bubbling jet mode. The emitted smoke was distributed around the experimental wire, and the dispersion range was small. As shown in Fig. 7b, when the thickness of the insulation was 0.4 mm, smoke was detected on the laser extinction camera at approximately 70 s. Similar to wire #1, at this time, the edge smoke emission stage had ended, and two bubbles were successively emitted and were dispersed to the adjacent wire region. After continuing to heat for some time, the bubble below also gradually increased and broke, and the emitted smoke swept over a large range of adjacent wire. When the insulation thickness was 0.5 mm, Fig. 7c shows that the moment when the smoke signal was detected was basically the same as that of wire #2, but a clear edge stable injection trajectory could be observed at this time, and this process lasted for more than 50 s. Through the above comparative analysis, the insulation thickness was found to an important factor affecting the emission time and concentration of edge smoke. With an increase in the insulation thickness, the beginning time of edge smoke emission was significantly delayed, but the duration increased. The reason for the reaction delay was that the thicker the insulation is, the more reactants there are, and the more energy needs to be accumulated before the reaction begins. The insulation thickness of wires #1 and #2 was so small that the concentration of smoke emitted at the edge was not enough to cause laser extinction, while the smoke emission trajectory could clearly observed for wire #3. In addition, the thicker the insulation is, the greater the tension that the outer surface can bear, and the later the bubbling time. More pyrolysis products accumulate in the bubble, so the smoke dispersion range is wider.

Figure 8 shows the variation of the average value of smoke concentrations with time for the above three wires. It can be seen that the smoke concentrations of all three wires will increase with time. Wire #1 may be first detected at an average concentration of 1.9 ppm, and then increased to 5 ppm. The start time of smoke emission for wire #2 and #3 is basically the same. After 120 s, a large amount of smoke is released and swept through the adjacent wire area and accumulated, so the smoke concentration suddenly increases. With the increase of the insulation thickness and the reactants, the smoke in the product increases correspondingly, resulting in more smoke in wire #2 and wire#3 than in wire#1.

**Effect of Overload Current on Smoke Emission Trajectory Characteristics under Microgravity**

Wire #2, #4 and #5 in Table 1 were selected to study the influence of the overload current on the smoke distribution. The three wires correspond different currents of 3.2 A, 3.9 A and 4.5 A respectively. The insulation is PE with thickness of 0.4 mm. As shown in Fig. 9, the detection times of the smoke signal under the three working conditions were 70 s, 20 s and 10 s, respectively. With the increase in current, the time needed to detect the smoke decreased significantly. By comparing wires #4 and #5, it can be found that when the current was 3.9 A, the wire experienced edge jet emission mode at 20 s. When the current was 4.5 A, bubble jet emission mode began at 20 s. Therefore, the larger the current is, the shorter the evolution time of edge jet emission is, and the start time of bubble jet emission is earlier. In conclusion, the overload current is an important factor affecting the anaerobic pyrolysis rate of insulation. The increase in current will cause the time smoke emissions occur to be earlier during insulation ignition. This can be attributed to the fact that the greater the current is, the greater the power of the wire core, and the faster the pyrolysis rate of the insulation.

Figure 10 illustrates the variation of the average smoke concentration with time for the three wires mentioned above. With other conditions are the same, the time of smoke detection is obviously advanced with the increase of current. The overall variation trend of smoke of the three wires is similar, and they all gradually increase from about 2 ppm. The rising
trend of wire #5 is more steep, because the high current increases the wire power and accelerates the emission of smoke, resulting in the rapid accumulation of smoke.

**Effect of Insulation Material on Smoke Emission Trajectory Characteristics under Microgravity**

Finally, the smoke distribution of overloaded wires with different insulation materials was analyzed. Wires #5, #6 and #7 in Table 1 corresponding respectively to PE, PTFE and PVC insulation materials were selected. The thickness of the PE and PVC insulation was 0.4 mm. The currents are 4.5 A. Due to the limitation of the experimental materials, PTFE insulation with a thickness of 0.15 mm was used in the experiment. The distribution of smoke emission trajectories of the three wires is shown in Fig. 11, indicating that there were significant differences among the three insulation materials. As demonstrated in Fig. 11a, the smoke emission of PE insulation was mainly the evolution of two modes. The symmetrical edge jet mode was reflected in the first 15 s of overload. Then, bubbles appeared at both ends successively. The bubbles increased continuously in the evolution.

![Fig. 11](image)

Smoke emission trajectory of wires with different insulation materials: a wire#5: 0.4 mm, PE, 4.5 A. b wire#6: 0.15 mm, PTFE, 4.5 A. c wire#7: 0.4 mm, PVC, 4.5 A.
process, ruptured and were generated again, and the bubbles gradually moved toward the middle of the wire. When the wire with PTFE insulation was overloaded, it mainly went through two stages as can be seen in Fig. 11b. Due to its good flame retardancy and low viscosity, unwrapping of the wrapped insulation occurred in the first stage. The second stage started at 40 s. The unwrapped insulation was wrapped around the metal wire core. After continuous heating by the current, the reaction began when the wire reaches the temperature required for pyrolysis, and a large amount of smoke was emitted and dispersed over a large space. In Fig. 11c, it can be noticed that the laser extinction signal was detected at 5 s for the overloaded wire with PVC insulation layer material, and a bubble burst and ejected products at approximately 10 s. Then, the smoke was gradually emitted along the insulation surface and dispersed to the adjacent wire region. It means that the stability of PVC insulation is the worst when the wire is overloaded in microgravity.

The experimental images after the experiments using the three insulation materials described above are shown in Fig. 12. There was a little solid residue observed after the reaction with the PE insulation, and approximately 3 mm of the insulation remained in the middle of the wire in an ellipsoid shape. After the reaction of PTFE insulation, there was no solid residue attached to the metal core, but a section of solid fragments after insulation unwinding was observed. Due to the disappearance of buoyancy in the microgravity environment, the debris was not removed in time and remained around the wire. This material is not involved in the pyrolysis reaction, so it cannot be regarded as a reaction residue. Therefore, PTFE insulation can be considered to have reacted completely. Large quantities of solid residues remained in the PVC insulation after the reaction and was wrapped around the metal core in a loose cylindrical shape. This showed that there were many impurities in the PVC insulation, resulting in an incomplete reaction.

The variation of smoke concentration with time for the above three wires is shown in Fig. 13. A significant difference in smoke emissions of the three wires can be clearly observed. Wire #5 and #6 corresponding to the insulation
materials PE and PTFE, the maximum value of the average smoke concentration during the experiments is lower than 10 ppm, while the wire #7 with PVC insulation material can reach 12 ppm. Combined with the results of Figs. 11 and 12, it can be seen that PVC is the most unstable when the wire is overloaded. It is the first material to react and release a large amount of smoke. At the same time, the carbon-chlorine bond with low activation energy breaks at the initial stage of overload, which may release HCl gas and seriously endanger the safety of astronauts. There are many impurities in PVC insulation so the reaction is incomplete and there are many solid residues. Generally speaking, PVC is not a suitable fireproof material in the space.

Conclusions

In this paper, the experimental data from the payload on board the SJ-10 satellite were processed and analyzed. According to the calculation results, the smoke distribution characteristics of two typical smoke emission modes in the early stage of overload wire insulations under microgravity were obtained, and the effects of insulation thickness, overload current and insulation material on the smoke emission trajectory characteristics under microgravity were clarified. The main conclusions are summarized as follows:

The smoke emission and distribution characteristics in the microgravity environment are significantly different from those on the ground. The edge smoke emission mode plays an important role in the early ignition under microgravity, determining the direction and concentration of smoke emission in the early stage. Quantitative analysis also reveals that the tendency of smoke to accumulate in a microgravity environment makes surrounding objects a potential fire risk. The bubbling jet smoke emission mode in microgravity can carry higher temperature products and spread over a larger area, significantly affecting the electronic and electrical components near the overload wires. This is a non-negligible space fire factor.

Smoke emission of overloaded wire insulation under microgravity will have different trajectories depending on the insulation thickness, overload current and insulation material. The insulation thickness is an important factor affecting the emission time and concentration of smoke at the edge. As the thickness of the insulation layer increases, the start time of the edge injection mode is delayed, and the duration of this process increases. The beginning moment of the bubble injection mode is delayed, more smoke products accumulate in the bubble, and a wider dispersion range is made after the release. The overload current is an important parameter affecting the anaerobic pyrolysis rate of insulation. With an increase in overload current, the power of the wire core increases, the pyrolysis rate of insulation increases, and each smoke emission moment is significantly advanced.

Different insulation materials produce different smoke emission trajectories when the wire is overloaded. The smoke emission of PE insulation is mainly the evolution of the edge smoke jet and bubbling smoke jet, and there is only a small amount of ellipsoid residue after the reaction; PTFE insulation successively undergoes two stages of untwisting and pyrolysis, and its flame-retardant performance is good. Moreover, it has a high purity and a complete reaction with almost no solid residues. PVC insulation materials have poor flame retardancy, emit a large amount of smoke, and may release HCl gas. Generally speaking, PVC is not a suitable fireproof material in space.
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