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Experimental Investigation on Thermal and Ignition Characteristics of Direct Current (DC) Series Arc in a Lab-Scale Photovoltaic (PV) System

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Abstract: This study investigates the thermal behavior and ignition dynamics of DC series arcs in a lab-scale photovoltaic (PV) system. The impacts of current magnitude, dynamic current variations, and electrode gap on electrode surface temperatures are analyzed, while ignition characteristics of common electrical materials (PC, PVC, XLPO, PPE, etc.) are investigated by analyzing critical time thresholds during the arc-induced combustion. Results show that electrode surface temperatures rise with increased current or larger electrode gaps, driven by the enhanced DC arc energy release. Dynamic current variations (increasing/decreasing) shift the balance between heat accumulation and dissipation, resulting in the nonlinear temperature evolution. Additionally, the peak temperature of the anode is about 50% higher than that of the cathode due to the electron flow-driven heat transfer and particle collisions. Notably, general electrical materials can be ignited successfully by stable DC arcs. The anode can ignite flame-retardant materials within 3 s, while the cathode takes a relatively long time to ignite, approximately 20 to 30 s. Besides, enlarged electrode gaps can induce a mutual reinforcement between arcs and flames, resulting in further stabilized arcs and intensified flames. This highlights potential elevated fire hazards as the connector gap increases due to the DC arc erosion.

Keywords: DC arcs; lab-scale PV system; thermal features; ignition dynamics; flame retardant materials

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Academic Editor: Jiaqiang E

Received: 1 April 2025
Revised: 20 April 2025
Accepted: 12 May 2025
Published: 16 May 2025

Citation: Wei, Z.; Liu, L.; Huang, W.; Yang, Y.; Zhen, H.; Lin, Y. Experimental Investigation on Thermal and Ignition Characteristics of Direct Current (DC) Series Arc in a Lab-Scale Photovoltaic (PV) System. *Fire* **2025**, *8*, 200. https://doi.org/10.3390/fire8050200

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1. Introduction

With the rapid development of the global economy over recent decades, countries' energy demand has surged considerably and then driven a continuous rise in carbon emissions. Due to obviously enhanced emissions of carbon dioxide, global warming is becoming increasingly prominent. In response to this climate crisis, many more efforts have been made to explore and develop renewable and sustainable energy [1]. Among various clean energy sources, solar energy is recognized as a promising renewable energy source to replace part of the traditional fossil fuels for electricity generation [2–5]. The photovoltaic (PV) industry has thus experienced explosive growth in recent decades [6]. However, the rapid scaling of PV infrastructure also exposes some critical safety risks [7]. For PV systems, especially widely distributed PV systems, the risks of electrical fires triggered by equipment defects, component aging, and poor maintenance can be enhanced significantly [8–10]. The frequently occurring fire accidents in PV systems worldwide indicate an urgent need to understand the ignition mechanism and fire spread evolution in PV systems, which can then help to evaluate the potential safety risks and prevent fire accidents in real PV systems.

In a 10 MW PV power station, even when neglecting other insulated components, the number of electrical contact points alone exceeds 80,000. Over prolonged operation, these contact points are susceptible to degraded connection reliability. Considering the high voltages and currents in PV systems, a poor connection has a high probability of inducing DC arc faults and then elevating ignition risks. Thus, DC arc faults have been accepted as the main reason for the fire accidents in PV systems [11]. In addition, compared to alternating current (AC) fault arcs, DC arcs give rise to sustained combustion and greater difficulty in terms of suppression [12]. This is caused by the absence of zero-current crossing, which ensures uninterrupted current flow and allows for continuous sustaining plasma energy within the arc. The relatively stable DC arcs can then establish an extremely high-temperature environment with the sustained thermal energy output, which can melt conductive materials, degrade insulation, and ignite adjacent combustible substances. Hence, investigation of the ignition dynamics of DC arc faults can be quite critical to elucidating the mechanisms underlying fire initiation and propagation in PV systems.

Several researchers have studied the diagnostic methods of DC arc faults in PV systems [13–15], which can be helpful in detecting DC arc faults by identifying the distinct features related to electrical signals, high-frequency noise, or optical radiation. However, the thermal and ignition characteristics of DC arcs are rarely investigated. Understanding the thermal and ignition characteristics of DC arc faults is pivotal for mitigating fire risks in PV systems, which can improve the understanding of the material flammability during the DC arcing and the ignition/flame-propagation dynamics. This can provide valuable insights into developing arc-resistant materials and formulating fire prevention and fighting methods. Zhang et al. [16] employed high-resolution imaging to analyze pine needle ignition under variable arc conditions, and determined a 50% ignition probability for pine needles under specific arc parameters by using logistic regression analysis. Ge et al. [17] performed analogous experimental studies to elucidate material ignition behaviors under AC arc faults. By testing the thermal characteristics of AC arcs, the heat transfer models to predict electrode temperature variations were established, while significant differences in heat transfer behaviors across materials were highlighted. Tartakowski et al. [18] explored the fire risks associated with arcing faults, particularly examining polypropylene and wood ignition under high-voltage and low-current arcing conditions. Irreversible material degradation and elevated fire probabilities were observed when arc durations exceeded 60 s, underscoring arc duration as a critical risk determinant. Du et al. [19] investigated the fire risks posed by AC arc faults in low-voltage systems. They proposed a quantitative model correlating arc energy with ignition probability, validated through experimental data. The study confirmed a strong positive correlation between arc energy magnitude and ignition likelihood, identifying arc duration as a decisive factor in fire initiation.

Guo et al. [20] experimentally evaluated the arc resistance of epoxy resin insulators with varying alumina filler contents under 8.5 kV/14 mA DC arc conditions and analyzed the thermal, mechanical, and chemical behaviors of these composites systematically. Takenaka et al. [21] conducted an experiment investigating the DC arc-induced ignition of polyvinyl chloride (PVC) under 100 V/13.5 A short-circuit conditions and revealed the dynamic responses of PVC and similar plastics to DC arc heating. Results demonstrated that rapid localized temperature escalation can induce the thermal decomposition of materials and subsequent ignition risks. Zhang et al. [22] performed experimental investigations to analyze the heat transfer and ignition characteristics of series fault arcs. A specialized model was developed to comprehensively describe the ignition process under varying operational conditions, which can be used to understand the thermal effects of fault arcs and their interactions with different materials.

With the much less related studies, ignition mechanisms of arc faults—particularly DC series arcs in photovoltaic (PV) systems—remain underexplored, representing a critical knowledge gap. Unlike AC arcs or general fault detection studies, DC series arcs generate high temperatures capable of inducing rapid material degradation and severe fire risks in real PV systems. A deeper understanding of the thermal characteristics and ignition dynamics of series DC arcs is essential to identify latent safety vulnerabilities, formulate targeted mitigation strategies, and refine design standards for PV systems. Addressing this gap will enable the development of robust safety protocols that account for variable operational conditions, thereby enhancing system reliability and fire prevention. As a result, further experimental studies are urgently needed to investigate the DC series arc ignition behavior and evaluate risk thresholds, which can support the creation of internationally harmonized safety frameworks for renewable energy infrastructures.

The objective of this study is to investigate the thermal performance and ignition processes of DC arcs in a lab-scale PV system, which can improve the understanding of the thermal response of metal connectors to the arcing and the capability of DC arcs to ignite general electrical materials. In this study, a lab-scale PV system will be established to simulate real PV systems, and the series DC arcs can thus be generated under conditions closer to real operating scenarios. The temperature variations of the electrode and ignition times of different materials will be measured experimentally in the study, and thermal and ignition characteristics of DC arcs will be investigated comprehensively under various conditions. The results obtained from this research are expected to provide more valuable insights into the ignition dynamics of real DC arc faults in PV systems.

2. Experimental Setup

The schematic of the DC arc ignition measurement system is shown in Figure 1a. The experimental setup primarily consists of a lab-scale PV system, a DC arc generator, a load circuit, a high-frequency oscilloscope, and a temperature measurement system. Series-connected PV panels are widely used to increase system voltage for improved efficiency and reduced losses, which is essential for meeting inverter input requirements, minimizing resistive losses through lower current operation, and reducing balance-of-system costs via thinner cables and fewer components. Hence, 12 PV panels were connected in series to establish a lab-scale PV system, which served as the power supply to generate the DC arcs. The adopted panel has an open-circuit voltage (Voc) of 22 V and short-circuit current (Isc) of 3.69 A; the lab-scale PV system has a Voc of 264 V and an Isc of 3.69 A. Compared to the stable DC power supply, the PV panel arrays can simulate the practical power supply conditions more accurately, considering that its energy output is dependent on the real solar irradiance. This can facilitate a more valuable simulation of the dynamic evolution process and related characteristics of the DC arc in the real-world PV systems.

The PV panel array was connected to the customized DC arc generator (MFT-AFCI-9000D) directly, which can achieve the precise control of DC arc energy by replacing electrodes and adjusting the electrode gaps. The DC arc generator supports voltage/current measurement ranges of 0–1500 V and 0–32 A, with a moving electrode distance of 100 mm and positioning accuracy of 0.1 mm/s. In the experiment, the adjustment of the electrode gap was controlled by a stepper motor with a step of 0.1 mm/s. During measurements, the electrodes contacted each other initially, and then the moving electrode was adjusted automatically via the control panel to establish the specified electrode gap. This automation process can ensure high precision in the electrode gap and provide stable experimental conditions for the generation and maintenance of dynamic DC arcs. Additionally, the brass electrode with a diameter of 8 mm was utilized to generate the DC arcs with an electrode gap of 2 mm in this study, which can ensure a relatively stable DC arcing process to facilitate

the measurements. A high-frequency oscilloscope (Keithley DMM6500 6 1/2, Tektronix, USA) was utilized to record the voltage and current changes over time during the whole DC arcing process. This oscilloscope has DC voltage/current measurement ranges of 100 nV–1010 V/10 pA–10.1 A with an accuracy of 0.002%/0.03%, while the sampling frequency can be varied from 3 Hz to 300 kHz. In this study, the sampling frequency of 50 Hz was used for measurements. This sampling frequency is sufficient to capture the characteristic voltage and current values in the lab-scale PV system, given that voltage/current dynamics are not the primary focus of this study. Furthermore, since the inherent instability of DC arcs can lead to significant fluctuations in voltage and current within a short period, the voltage and current were recorded continuously under a specific condition for an extended period, and the time interval between each measurement was about 5 min to guarantee full electrode cooling. The data were then averaged to determine the characteristic parameters of current and voltage for investigating characteristics of DC arcs under different conditions.

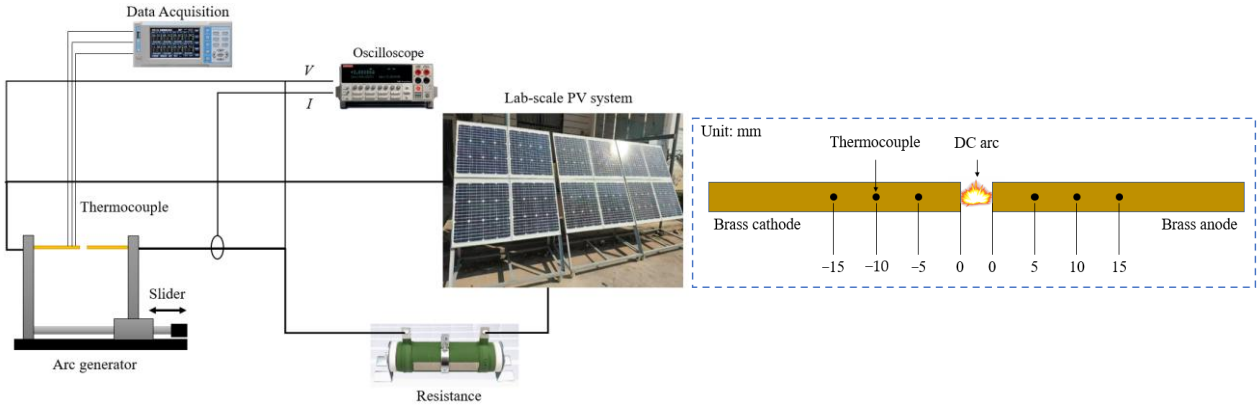


Figure 1. The schematic of the DC arc ignition measurement system. (**a**) Experimental setup; (**b**) Locations of thermocouples.

Additionally, in order to thoroughly investigate the ignition behavior of DC arcs, six K-type thermocouples were arranged on the electrode surfaces to measure temperature variations during the DC arcing. The measured temperature data were recorded at a frequency of 1 Hz using a multi-channel temperature recorder (TCP-32 XL, Measure Fine, CN), which has a measurement accuracy of 0.2%, a sampling rate of 0.1–999 SPS, and supports various thermocouple types (K, S, R, etc.). Given the extremely high temperature of DC arcs and the limited measurement range of thermocouples, the thermocouple closest to the DC arc was positioned 5 mm from the electrode tip, while the remaining thermocouples were located with an interval of 5 mm along the electrode surface, as shown in Figure 1b. To measure temperature distributions on the electrically energized electrodes accurately, ungrounded thermocouples were employed in the experiment. In these thermocouples, the temperature sensing junction and the protection tube are fully insulated, thereby eliminating the interference from the electrode current completely. To investigate the ignition characteristics of DC arcs comprehensively, several materials commonly used in PV systems and easily found in the surrounding environment were adopted to test their ignition features during the DC arcing. Furthermore, during the ignition tests, the time nodes of DC arc generation, as well as the initial appearance of smoke and visible flames of different materials, were recorded to facilitate the in-depth analysis of ignition characteristics of DC arcs on different materials. To ensure measurement accuracy, each test was repeated at least five times under a constant condition. With the averaged data, using a 95% confidence level [23], the uncertainties are 0.9% in the voltage, 1.2% in the current, 2.6% in the temperature, and 3.4% in the ignition times.

3. Results and Discussions

3.1. General Temperature Distributions of the Electrode During the DC Arcing

Figure 2 illustrates variations in electrode surface temperatures during the occurrence of a DC arc generated by the lab-scale PV system with the energy output of 244 V and 0.27 A. The ambient temperature, serving as a baseline reference, remains stable at about 25 °C throughout the measurement. As shown in the figure, the temperature rise is most pronounced at the closest measured location, which is 5 mm from the arc, where the peak temperature approaches around 140 °C. Specifically, within the first 200 s, the temperature increases rapidly and then fluctuates at a high level. When the power is cut off around 460 s, the temperature gradually decreases due to the lack of thermal input from the DC arcs. This indicates the significant thermal impact of the DC arc on areas near the arc source owing to the fast heat transfer to the electrode surface through conduction and radiation, which causes the sustained heating in the local area.

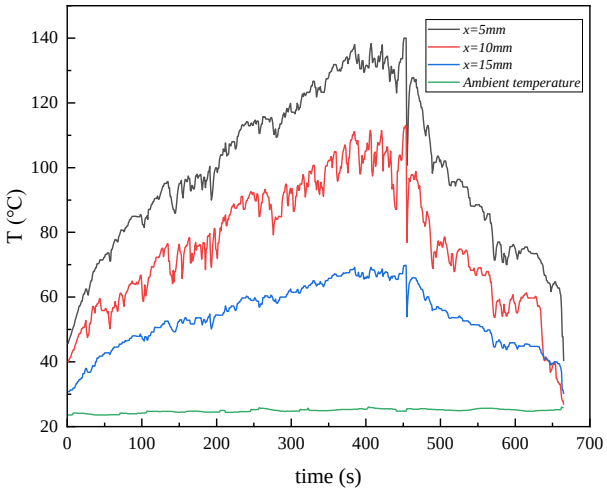


Figure 2. Surface temperature variations of the electrode connected to the positive terminal under the condition of 244 V and 0.27 A.

Compared to the position at 5 mm, the rise rate and peak value of temperature are comparatively lower at the position of 10 mm, with a peak temperature of about 110 °C, while the temperature curve still shows a similar trend with relatively obvious fluctuations. The temperature fluctuations indicate the still-intense thermal impact of DC arcs, while the lower temperatures suggest the heat transfer attenuation at this slightly farther distance. At the position of 15 mm, the temperature rise is even slower, with a peak temperature of only around 65 °C. This suggests that heat transfer at this distance should be primarily through conduction, with minimal direct influence from arc radiation. The smaller temperature fluctuations imply the reduced thermal influence of DC arcs and a relatively stable thermal distribution in this area.

As a result, the electrode surface temperature decreases rapidly with increasing distance from the arc source, indicating a significant reduction in thermal impact at farther distances. The notable heating effects at the 5 mm and 10 mm positions from the arc highlight the intensive local heating caused by the high energy released by the DC arc. At 15 mm, the attenuation trend of thermal effect can be determined by the arc's energy radiation range, the mode of heat propagation in the medium, and the thermal conductivity of the electrode material. Among these factors, the thermal conductivity of the electrode material should play a crucial role, as it dominates the efficiency and speed of heat transfer from the arc source to the electrode surface. Moreover, it is noted that more fluctuating temperature data indicate the great instability of DC arcs in real PV systems. The signifi-

cant thermal effects caused by the DC arc indicate its potential severe hazards, leading to fire accidents.

For the PV system under a condition of 244 V and 3.2 A, the surface temperature variations of positive and negative electrodes are compared in Figure 3. It is seen that, during the DC arcing process, the electrode surface temperature peaks in the negative electrode region (−5 mm, −10 mm, −15 mm) are generally lower than those in the positive electrode region (5 mm, 10 mm, 15 mm). Additionally, the temperature distributions of positive/negative electrodes exhibit similar variation trends. The closer the distance to the DC arc, the faster the temperature rises, and the higher the peak temperature. Specifically, at the 5 mm position near the DC arc on the positive electrode, the temperature increases rapidly and reaches a peak of nearly 300 °C, accompanied by significant fluctuations. This indicates that the closer area is strongly affected by direct heat conduction and radiation from the DC arc. As the distance increases, the peak temperature gradually decreases to approximately 230 °C at the 10 mm position, while it drops to about 100 °C at the 15 mm position. In contrast, the maximum temperature peak in the negative electrode region is about 250 °C at the −5 mm position, while the lowest temperature peak at the −15 mm position has a similar level to that at the 15 mm position. It is thus concluded that, either in the positive or negative electrode regions, rapid temperature attenuation trends with the increased distance always exist, which further confirms that the thermal effect of the DC arc prefers to concentrate around the DC arc and diminishes effectively with distance owing to the cooling effects of ambient air.

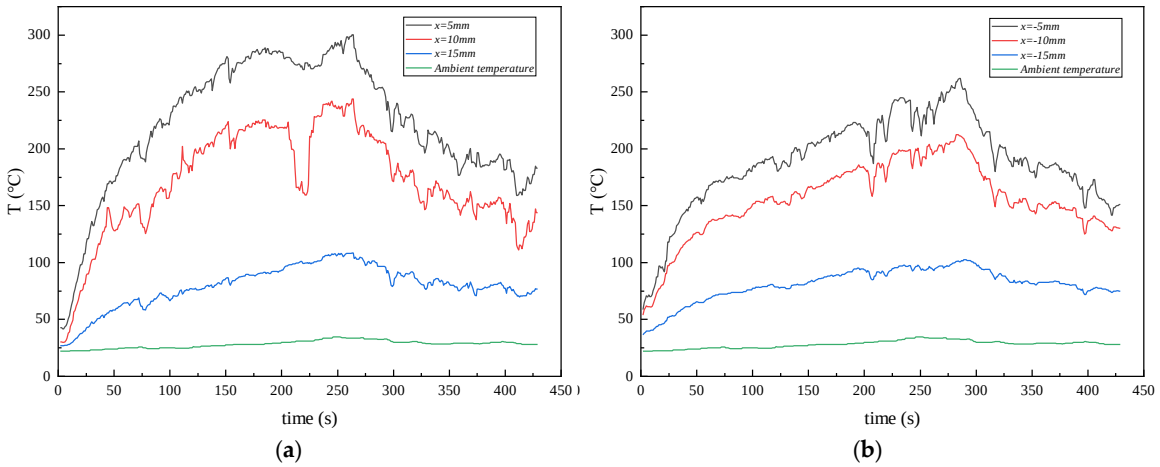


Figure 3. Comparison of surface temperature variations of electrodes connected to the positive/negative terminals under the condition of 244 V and 3.2 A. (**a**) Positive electrode; (**b**) Negative electrode.

Furthermore, it is noted that there exist obvious differences in thermal effects between the positive and negative electrodes owing to the different temperatures at the same distances away from the DC arc, as shown in Figure 3, such as at 5 mm and −5 mm positions. This indicates more significant heat accumulation in the positive electrode region, which can be caused by more effective heat transfer and particle collision, accompanied by the electron flow toward the positive electrode. Due to the higher temperatures and large fluctuations in the positive electrode region, the physical and chemical properties of the materials may be affected more significantly. Particularly under stable high-intensity DC arc conditions, the structural stability and durability of the positive electrode material may decline more notably than the negative side. By contrast, for the negative electrode region, although the heat accumulation is relatively weaker, the potential long-term thermal aging of materials due to DC arcs should not be neglected in real PV systems. Moreover, the higher temperatures in the positive electrode region also imply higher fire risks for the components

connected to the positive terminal of the PV system. As a result, for PV systems, special attention might be paid to optimizing the heat resistance of connectors in the positive electrode region in order to improve system reliability and prevent fire occurrence.

3.2. Effects of Current on Electrode Temperatures During the DC Arcing

Figure 4 illustrates the variations in the electrode surface temperature with the varied current input at a constant position of the positive electrode. To examine the effects of varying current, measurements are conducted on the lab-scale PV system at different times of the day, and then four distinct current conditions (3.2 A, 1.8 A, 1.4 A, and 0.27 A) are produced for investigating the thermal effects of DC arcs. As shown in Figure 4, with a current of 3.2 A, the temperature rises the fastest and reaches the highest peak. Within the first 50 s of the sustained DC arc, the temperature sharply increases to approximately 180 °C. The temperature continues to rise at a slower rate, reaching the peak value of about 300 °C, eventually at around 260 s. Additionally, the temperature curve shows more evident fluctuations after 100 s, which may be caused by coupling effects of the dynamic instability of the DC arc, changes in the DC arc channel, and the uneven local heat conduction. Furthermore, as the current is decreased steadily, the rising trend of temperature within the first 50 s becomes increasingly moderate, while the peak temperature is also decreased to about 70 °C at a current of 0.27 A during the measurement period. It is thus known that the larger current intensifies the heat release process of the DC arc effectively, causing the local area of the electrode to endure strong heat accumulation effects.

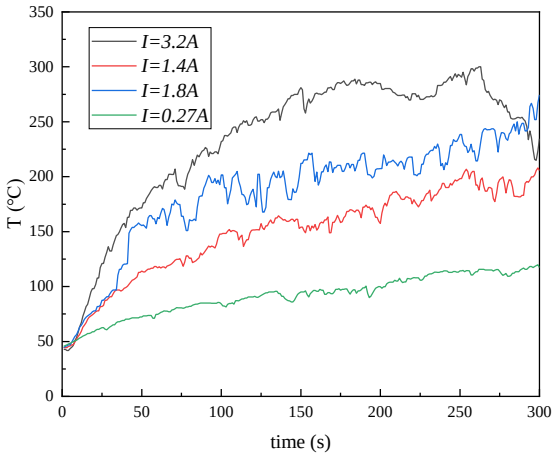


Figure 4. Effects of current on the surface temperatures at the 5 mm position in the positive electrode region.

Considering that the current of real PV systems is variable with changes in environmental conditions, there exists a need to investigate the dynamic impact of current variations on the thermal effects of DC arcs on electrodes. This can provide a comprehensive understanding of the thermal characteristics of DC arcs. To quantify the effects of current variability, experimental measurements are carried out under cloudy sky conditions, which can induce continuous current changes in the PV system owing to the natural irradiance fluctuations. The dynamic responses of surface temperatures to the continuous decreased/increased current in the tested PV system are illustrated in Figures 5 and 6. As shown in Figure 5, as the current is varied from a high value to a low value, accompanied by the stable DC arc, the electrode surface temperature does not exhibit a simple linear decline but rather shows an initial rising trend followed by a gradual decrease. Throughout the current variation process, the temperature curve over time exhibits a distinct peak interval, where the electrode surface temperature reaches its highest value under a certain medium current condition. In contrast, when the current increases gradually, the temperature variation

trend of the electrode shows an approximately linear upward trend without a noticeable temperature peak, as shown in Figure 6.

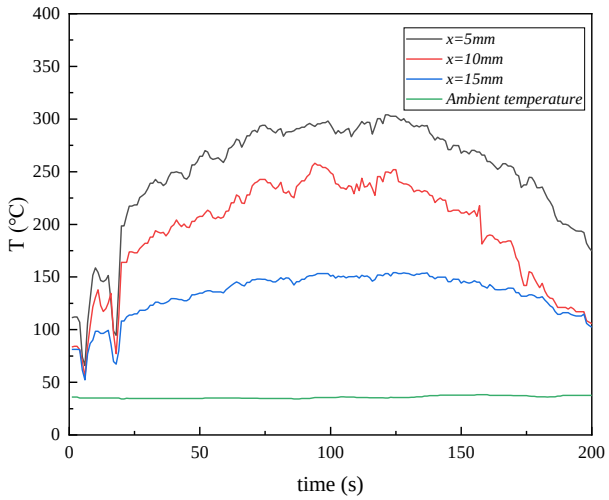


Figure 5. The variations of the electrode surface temperature with the decreased current (3.1 A → 1 A) in the lab-scale PV system.

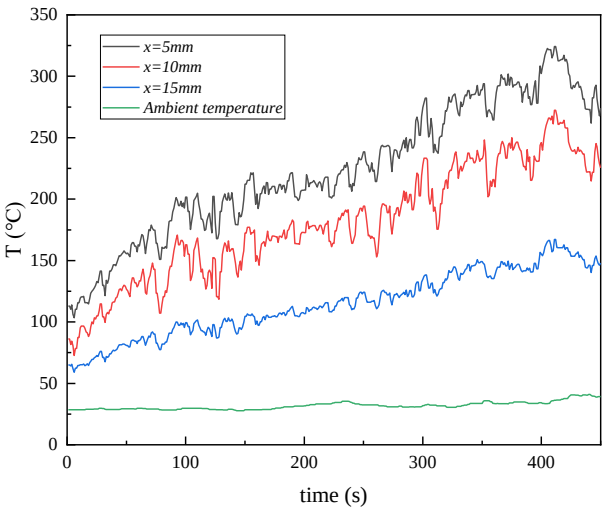


Figure 6. The variations of the electrode surface temperature with the increased current (1.8 A → 2.43 A) in the lab-scale PV system.

Generally, the heat generated by a DC arc is proportional to the square of the current passing through it. Therefore, changes in current can directly affect the heat transfer state and temperature distribution of the electrode. When the accumulation and dissipation rates of heat in the electrode are not balanced perfectly, the electrode's ability to reach thermal equilibrium can be influenced considerably, which thereby affects the variation trends of electrode surface temperatures. This finally predominates the significant differences in temperature variation trends under different current change paths, as shown in Figures 5 and 6. Specifically, when the current decreases continuously to a low level, the initial high current results in a substantial amount of heat generated by the DC arc, causing a quite high rate of heat accumulation in the electrode during the initial stage. As the current decreases gradually, the heat generation rate is reduced steadily while the heat dissipation rate is accelerated comparatively. However, the large amount of heat generated by the DC arc in the early stages is still sufficient to maintain a rapid upward trend in the electrode surface temperature until the current drops to a certain level. Under this condition, the balance between the heat dissipation and the heat generation is reached,

and then the temperature begins to decline gradually owing to the further reduced heat generation by the continuously decreased current. As a result, this thermal hysteresis effect should be the main reason for the nonlinear variation trend of surface temperature with the dynamically reduced current. By contrast, when the current increases steadily during the DC arc process, the heat generated by the DC arc increases progressively with the increased current, leading to an increasingly effective heat accumulation process in the electrode. However, the heat dissipation rate could maintain a relatively steady level after an initial acceleration owing to the relatively stable ambient cooling effects. Consequently, the electrode surface temperature shows a steady linear rising trend with the dynamically increased current during the DC arc process, as shown in Figure 6. Overall, dynamic fluctuations in the current of a PV system can exert complex effects on the thermal performance of a DC arc. With the sustained DC arcs, the dynamic balance point between the heat accumulation and dissipation changes continuously with the varied current, predominating the complex evolution of the DC arc and resulting in the nonlinear temperature variation trend in the electrode.

Based on the above measured data, it is known that the current plays a crucial role in the temperature rise trend of electrodes during the DC arcing process. Higher currents give rise to strong thermal effects of the DC arc, causing a rapid increase in electrode temperature accompanied by significant temperature fluctuations. Such intense thermal effects can have profound impacts on material properties, which can cause thermal fatigue, local damage, and microstructure degradation of the electrode material. In contrast, under lower current conditions, even though the thermal effects of the DC arc are weakened significantly, the comparatively stable DC arcing process can still lead to the continuous heat accumulation in local areas and then the higher local temperature of the electrode. This can also exert a significant influence on the material properties of connectors. Apart from this, considering the quite high temperature distributions of the electrodes under either high or low current conditions, the thermal effects caused by the DC arc can always pose potentially severe risks of localized ignition and fire accidents in the PV systems.

3.3. Effects of the Electrode Gap on Temperatures During the DC Arcing

During the DC arcing, the thermal effects can lead to the melting of metal components, causing a larger gap between connectors. The analysis of the thermal performance of the DC arc with the increased gap can improve the understanding of the dynamic variations of the DC arc and help to evaluate risks of DC arcing. Figure 7 illustrates the temperature variations at the 5 mm position of the positive electrode under 244 V and 3.2 A conditions at different electrode gaps (Δx = 1 mm, 2 mm, 3 mm). The experimental data indicate that the electrode gap significantly affects the rise rate of temperature, temperature peak, and temperature fluctuations.

When the electrode gap is 1 mm, the electrode surface temperature rises relatively slowly and reaches the lowest peak value of about 170 °C at 100 s. During the rising trend, the comparatively smaller fluctuations can be observed. Furthermore, as the electrode gap increases to 2 mm or 3 mm, the increasing rate and peak value of temperature are both enhanced significantly, with the peak values reaching about 220 °C/280 °C at 100 s. Furthermore, temperature fluctuations become more obvious compared to those at the 1 mm gap. These variations can be explained briefly as follows. In shorter electrode gaps, due to the smaller length of the DC arc, the spatial diffusion range of heat is limited considerably. Meanwhile, the lower equivalent resistance of the DC arc results in relatively less heat release during the DC arcing. This results in comparatively moderate but more uniform localized heating of the electrode, which finally leads to the lower peak value and relatively less fluctuations of the electrode surface temperature during the arcing process

in shorter gaps, as shown in Figure 7. As the electrode gap is increased, the increased DC arc length brings about the increased resistance and then the significantly increased heat release by the DC arc. This can contribute to the faster rise and higher maximum value of the surface temperature, as shown in Figure 7. Besides, it is noted that although the larger electrode gaps can lead to the increased thermal energy release, the increased arc length can weaken its stability during the DC arcing, owing to airflow disturbances and arc flickering exacerbating the unevenness of heat transfer. This leads to the relatively larger fluctuations of electrode temperature and may give rise to localized overheating of the electrode, as shown in Figure 8. Specifically, the crater and black ablation marks within the red circles in Figure 8 are the results of localized high-temperature effects caused by DC arcing.

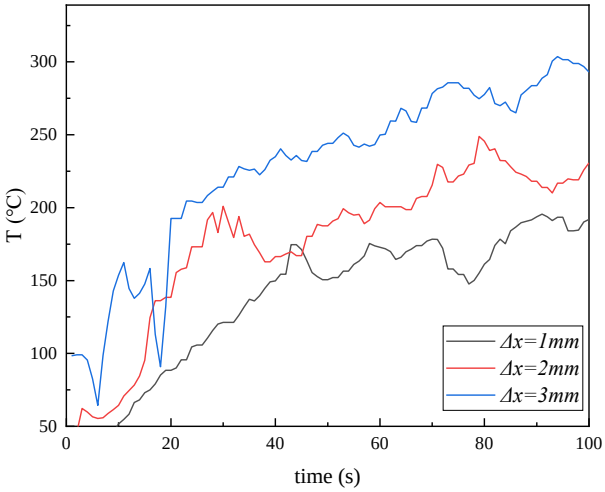


Figure 7. The effects of the electrode gap on surface temperatures at the 5 mm position in the positive electrode region under the condition of 244 V and 3.2 A.

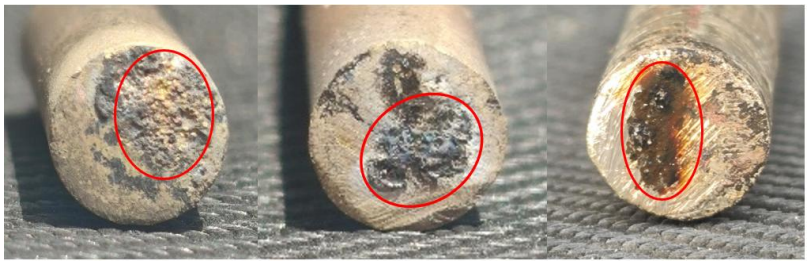


Figure 8. Localized overheating phenomenon of the electrodes due to the DC arcing.

3.4. Ignition Characteristics of the DC Arcs

To further evaluate the thermal effects of DC arc and its potential fire risks in PV systems, the ignition times of typical materials used in PV systems are measured to gain useful knowledge of the DC arc characteristics in real PV systems. By using the lab-scale PV system under the condition of 244 V and 1.2 A, some materials commonly used in PV system components are adopted to measure their ignition times during the DC arcing, including polyphenylene ether (PPE), polycarbonate (PC), silicone rubber, cross-linked polyolefin (XLPO), polyvinyl chloride (PVC), and polyethylene (PE). The fundamental properties of these electrical materials are given in Table 1. Additionally, paper and leaves, two materials commonly found in the surrounding environment of PV systems, are also chosen to study their ignition characteristics during the DC arcing. These materials not only cover various electrical insulation materials of common PV system components but also consider some potential combustible materials in the environment. This can provide more valuable data support for a comprehensive investigation of the ignition capability

of DC arcs, which can then provide useful theoretical guidance and practical basis for the safety design and risk assessment of PV systems.

Table 1. The fundamental properties of electrical materials tested in this study.

Materials	PPE	PC	Silicone Rubber	XLPO	PVC	PE
Melting point °C	268	220–230	-	120–180	212	85–136
Thermal Conductivity W/(m·K)	0.22–0.25	0.19	0.2–3.0	0.2~0.3	0.14–0.17	0.33–0.52
Dielectric Constant F/m	2.5–2.7	2.8–3.2	2.8–3.5	2.3–2.5	3.0~5.0	2.2–2.4
Ignition point °C	450–550	550–650	400–450	≥350	250–350	340–380

As shown in Figure 9, under the measured condition of 244 V and 1.2 A, all materials are ignited successfully by the DC arc, and visible flames can be observed and sustained. Despite excellent anti-ignition properties under normal conditions, flame-retardant materials (such as PPE, XLPO, and silicone rubber) all ignited comparatively easily, owing to the sustained high-temperature and high-energy effects of the sustained DC arcs. Furthermore, it is observed that these flame-retardant materials typically produce visible flames within seconds to tens of seconds as they are exposed to the DC arc. After the ignition, the open flame can be highly persistent, indicating that the heat transfer and energy input from the intensive DC arc exceed the critical values of their flame-retardant performance. More specifically, high-energy DC arcs deliver localized heat fluxes that exceed the thermal resistance limits of flame-retardant components. Although these components initially inhibit combustion through endothermic reactions and radical quenching, the sustained arc energy can disrupt their protective mechanisms by continuously breaking polymer bonds and releasing flammable volatiles. Once pyrolysis begins, the process becomes self-sustaining: heat transfer from both the arc and nascent flames accelerates the degradation of adjacent materials. This finally leads to the sustained flames, despite the presence of inherent flame-retardant properties. In contrast, materials like paper and leaves commonly existed in the environment exhibit obvious flammability. During the DC arcing process, these materials can be ignited in a relatively short time (within about 6 s) and then form bright flames quickly. The rapid ignition should be mainly caused by the relatively low ignition temperature and comparatively high volatility of these materials. For materials tested in this study, with the coupling effects of thermal radiation and conduction from the DC arc, the combustible components in the materials decompose rapidly and react with oxygen in the air to form the sustained open flames. For the better clarification, critical time points for the ignition processes of these tested materials are provided in Table 2.

Table 2. The ignition times of different materials with the DC arcing under the condition of 244 V and 1.2 A.

Materials	PPE(+)	PC	Silicone Rubber	XLPO(+)	PVC	PE	Paper	Leave
Arc start (s)	0.12	2.18	0.1	1.09	2.19	2.11	2.16	2.15
Smoke (s)	3.04	19.4	17.2	3.03	10.07	4.15	9.11	5.16
Fire (s)	3.11	33.08	21.1	3.16	36.1	9	20.07	8.18
Ignition time (s)	2.99	30.9	21	2.07	33.91	6.89	17.91	6.03

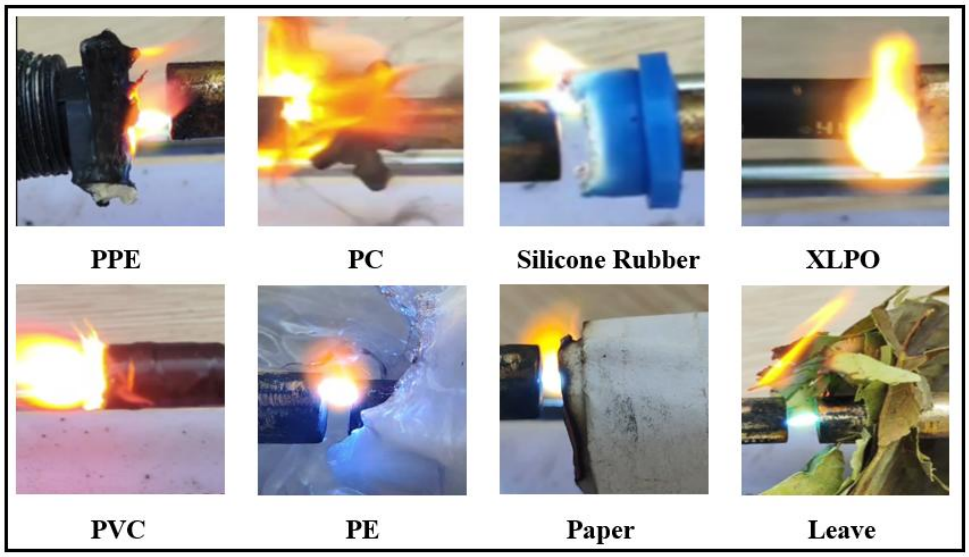


Figure 9. Ignition conditions of different materials during the DC arcing under the condition of 244 V and 1.2 A.

Additionally, to better clarify the effects of variable conditions in the PV system on the ignition processes of different materials, the ignition times of these materials are also measured under the condition of 243 V and 2.9 A. As illustrated in Tables 2 and 3, the ignition times of the tested materials are reduced significantly. For example, the ignition times of PC and PVC decrease considerably from around 30 s to approximately 10 s. Based on the earlier investigation of the current's effects on electrode surface temperatures, it is known that higher currents enhance the heat release capability of DC arcs, thereby significantly increasing the electrode surface temperature. This leads to a notable reduction in the ignition times of these materials, as shown in Tables 2 and 3. Hence, these results further confirm that higher currents can substantially increase the ignition risks associated with DC arcs in PV systems.

Table 3. The ignition times of different materials with the DC arcing under the condition of 243 V and 2.9 A.

Materials	PPE	PC	Silicone Rubber	XLPO	PVC	PE	Paper	Leave
Arc start (s)	1.15	1.01	2.08	2.03	1.06	2.08	7.04	0.11
Smoke (s)	4	3.11	4.14	2.08	4.07	6.04	10.14	2.01
Fire (s)	15.14	12.89	13.09	6.15	14.02	7.01	17.19	3.07
Ignition time (s)	13.99	11.88	11.01	4.12	12.86	4.93	10.15	2.96

Moreover, it is noted that the ignition times of PPE and XLPO materials are significantly shorter by an order of magnitude compared to other materials, as shown in Table 2. Additionally, even under the higher current condition as shown in Table 3, these two materials still exhibit much longer ignition times than under the relatively lower current condition as shown in Table 2. This is attributed to the fact that these two materials are in direct contact with the positive electrode during the DC arcing under the condition of 244 V and 1.2 A (Table 2). As discussed earlier, the positive electrode region of the DC arc has a much higher temperature due to its more effective heat accumulation effect. This not only significantly increases the surface temperature of the materials but also accelerates the reaction of combustible gases produced by the material decomposition with the higher temperature environment, eventually leading to the extremely rapid ignition of the materi-

als. It is thus known that, once a DC arc occurs in actual PV systems, the risks of ignition and flame spread can be much higher in the positive electrode region than the negative electrode region.

Overall, under high voltage and large current conditions, a stable DC arc can not only ignite insulating and sealing materials quickly in PV systems but also has a high possibility of inducing sustained open flames to ignite other combustible materials in the surrounding environment. The ignition capability of such high-energy DC arcs on different materials is closely related to the material's pyrolysis characteristics, surface thermal conductivity, and flame-retardant properties. It is noteworthy that, under relatively lower current conditions, although the time required to ignite different materials becomes longer, the heat accumulation effect of the sustained DC arc on the materials still has a high possibility of resulting in the open flame phenomenon. This can also obviously increase the potential risks of further flame propagation and then trigger the larger-scale fire spread.

The material loss after the ignition can increase the connector gap during the DC arcing, which can influence the DC arc characteristics effectively, and then the ignition features. In consideration of this, the effects of increased electrode gaps on the ignition processes of DC arcs on different materials are investigated in this part. As shown in Figure 10, when the ignited materials are moved away gradually with the increased electrode gap, the DC arcing is not weakened but intensified significantly, accompanied by the greater brightness and stability. Furthermore, it is noted that the flames of the ignited materials also become more intense after increasing the electrode distance. This indicates that the increased electrode distance does not weaken the energy transfer of the DC arc but instead further strengthens its thermal effects.

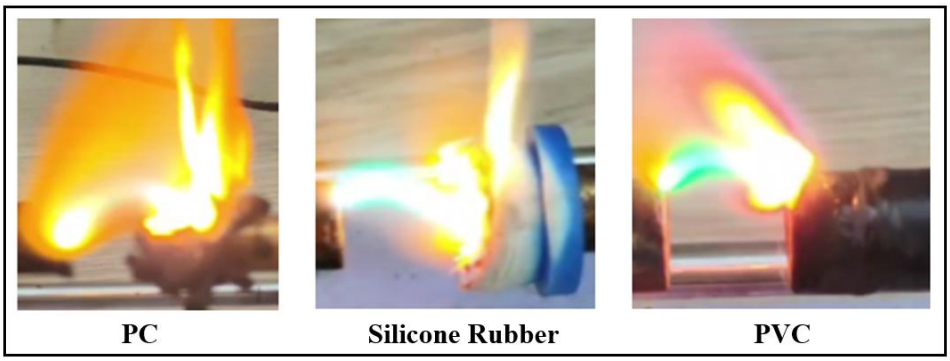


Figure 10. Combustion conditions of different materials during the DC arcing with the increased electrode gap under the condition of 244 V and 1.2 A.

This phenomenon could be codetermined by the self-stabilizing characteristics of a DC arc and its complex dynamic interaction with the surrounding environment. When the electrode distance increases, the electric field strength gradient between the two poles of the DC arc increases, which gives rise to higher ionization efficiency within the DC arc and generates more plasma particles. These high-energy plasma particles can maintain and enhance the heat generation of the DC arc, allowing the DC arc to remain stable over longer distances. Additionally, the volatile gases released during the combustion of ignited materials may also play an important role. These gases not only provide additional conductive channels for the DC arc but also supply chemical energy to sustain its high-temperature environment, which contributes to the enhanced brightness and temperature of the DC arc. Meanwhile, the enhanced DC arc can also promote the flames of the ignited materials significantly. The high temperature and strong thermal radiation effects brought by the stretched DC arc can accelerate the volatilization and oxidation reactions of combustible components on the material surface. This can thus contribute to the increased

size and rapid spread of flames, which can then accelerate the ignition of other flammable materials, as shown in Figure 10.

This phenomenon indicates that the increased electrode gap due to the consumption of materials may further intensify the DC arcing, which can, in turn, promote the open flame, eventually posing a higher risk of fire spread through the mutual promotion of open flame and the DC arc.

4. Conclusions

This study investigates the thermal and ignition characteristics of DC arcs in a lab-scale series PV system. The effects of current, the dynamic variations of current, and electrode gap on the electrode surface temperatures during the DC arcing are analyzed quantitatively. In addition, the ignition characteristics of DC arcs on several commonly used electrical materials are studied quantitatively by measuring the critical time nodes of their ignition processes. The results obtained in this study can provide useful insights into enhancing system reliability and fire prevention of PV systems. The main results are concluded as follows.

1. With an increased current or a larger electrode gap, the thermal effects of DC arcs can increase surface temperatures of the electrode by up to about 100% due to the enhanced heat release from DC arcs. Furthermore, the rapid dropping trend of temperature along the electrode surface indicates the localized overheating phenomenon near the electrode tips, determined jointly by the arc's energy radiation range, the mode of heat propagation in the medium, and the thermal conductivity of the electrode material. Moreover, the positive electrode is found to have much higher temperatures than the negative electrode, which is attributed to the more effective heat transfer and particle collision accompanied by the electron flow toward the positive electrode. This highlights the higher ignition risks in the region connected to the positive terminal of the PV panels.
2. Notably, as the DC arc sustains, pronounced heat accumulation can still occur under conditions of continuously decreased or increased current induced by sudden weather changes. This creates a high-temperature environment that may also elevate ignition risks in PV systems under variable weather conditions. With sustained DC arcs, the dynamic balance point between heat accumulation and dissipation shifts continuously with the varied current, which governs the complex evolution of the DC arc, resulting in a nonlinear temperature variation trend on the electrode.
3. The electrical materials (PPE, PVC, XLPO, etc.) used in the PV systems, as well as the combustible materials in the surrounding environment (paper and leaves), can be ignited within 30 s by the stable DC arcs and exhibit obviously sustained open flames. Furthermore, during the DC arcing, the ignition capability of the positive electrode can be much higher than the negative electrode due to its much higher temperature environment, which reduces the ignition time from tens of seconds to approximately 2 s. The high-energy arc's ignition capability is closely related to the material's pyrolysis characteristics, surface thermal conductivity, and flame-retardant properties. Additionally, even under relatively low-power conditions, the sustained DC arc can still ignite materials and induce open flames owing to continuous heat accumulation.
4. During the DC arc ignition process, a synergistic coupling effect between the DC arc and open flame is found when the electrode gap is enlarged. The expanded gap establishes a positive feedback mechanism: the open flame provides a high-temperature environment to improve the DC arc stability, while the intensified DC arc discharge releases more heat to promote the material pyrolysis and then amplifies the open flame's intensity. This mutual reinforcement leads to progressively stronger

arcing phenomena and larger flame development. From a fire safety perspective, as the connector materials are consumed by the weaker DC arcs, the increased connector spacing has a certain possibility to significantly aggravate fire hazards through the mutual reinforcement of DC arcs and open flames.

Since this study focuses on current variation effects in the lab-scale PV system, the effects of electrode material are not analyzed in this study. As the electrode material can also affect the stability and intensity of DC arcs in PV systems significantly, its effects should be further investigated in future work. Such research would help to further improve a comprehensive understanding of DC arc characteristics in PV systems and facilitate safety optimization for critical components.

Author Contributions: Conceptualization, Z.W.; Methodology, L.L. and W.H.; Validation, W.H. and Y.Y.; Formal analysis, Z.W. and Y.Y.; Investigation, L.L. and W.H.; Data curation, L.L.; Writing—original draft, Z.W.; Writing—review & editing, H.Z.; Visualization, Y.Y.; Supervision, H.Z. and Y.L.; Project administration, Y.L.; Funding acquisition, H.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The Authors thank the Fire and Rescue Department of Haikou City for the financial support (HD-KY-H-2024237) of this study.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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