

Article

Experimental Investigation of Thermal Response of Single-Glass Photovoltaic Modules with Different Inclination Angles

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Abstract

In order to achieve the goal of carbon neutrality, the installed capacity of photovoltaic (PV) modules has been increasing rapidly. In particular, single-glass PV modules are widely deployed in both utility-scale and distributed PV power generation systems. However, single-glass modules are highly susceptible to internal faults (e.g., direct current arc faults and hotspot faults) and external fire sources (e.g., wildland fires and rooftop fires), which may lead to simultaneous burning of the modules and adjacent combustibles, thereby promoting large-scale fire spread and causing severe economic losses. In this study, a dedicated experimental platform was developed to systematically investigate the fire behavior of single-glass PV modules under exposure to a pool fire. Systematic fire experiments were conducted to investigate the influence of module inclination angle and tempered glass integrity on the burning process, molten dripping flame behavior, and temperature-rise characteristics of single-glass PV modules. The results show that the integrity of the front glass has a pronounced effect on the burning behavior. At the same inclination angle, cracked modules exhibit significantly faster fire growth and higher temperature-rise rates than intact modules, while also being more susceptible to rapid burn-through by the external fire, accompanied by the generation of numerous molten dripping flames. In addition, the module inclination angle has a significant influence on the fire behavior of PV modules. As the inclination angle increases, the fire development rate, temperature-rise rate, and average burning duration of dripping flames all display a non-monotonic trend of first increasing and then decreasing, reaching their maxima at an inclination angle of 15°. These findings provide a theoretical basis for the fire protection design and fire risk assessment of PV power generation systems and are of practical significance for enhancing their operational safety.



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Keywords: PV modules; temperature characteristics; fire damage behavior; inclination angle; pool fire

1. Introduction

As the global economy grows rapidly and awareness of decarbonization deepens, the application of conventional fossil fuels is facing increasing constraints due to resource

depletion and environmental concerns, leading to a pronounced mismatch with the continuously rising global energy demand. As a clean, renewable, and scalable energy source, solar energy has attracted widespread attention and deployment. According to data from the International Energy Agency (IEA), the global annual new photovoltaic (PV) installed capacity had surpassed 500 GW by the end of 2024, and the average annual incremental PV capacity is projected to maintain a stable level of 540 GW throughout the period up to 2035 [1]. In particular, single-glass PV modules are currently the most widely used type of PV module worldwide [2] and are extensively deployed in utility-scale PV power plants and rooftop PV systems [3,4]. However, in recent years, PV fire accidents have occurred with increasing frequency, particularly in PV power generation systems installed in open-field sites, on building rooftops, and in other exposed environments [5,6]. According to statistics, the annual fire incident frequency of PV systems is approximately 0.0289 fires per megawatt of installed capacity [7]. When direct current arc faults or hotspot faults occur during the operation of PV modules, heat accumulation within the module can readily lead to spontaneous ignition of the module itself [8]. Moreover, localized overheating can lead to cracking of the surface glass of PV modules [9], and the ignited components may in turn ignite adjacent combustibles, thereby promoting fire spread within the PV array [10]. Notably, photovoltaic (PV) modules subjected to long-term outdoor exposure exhibit significant degradation, rendering them prone to glass cracking [11,12]. For example, a previous study on rigid PV modules that had been in operation outdoors for 22 years in India revealed that approximately 25% of the modules exhibited glass damage, and the associated fire risk factor increased dramatically [13]. Therefore, elucidating the fire characteristics of single-glass PV modules with intact and cracked front glass under external fire exposure is of great significance for ensuring the safe operation and sustainable development of PV power plants.

In recent years, research on the fire characteristics of PV systems has focused primarily on intact PV modules. Wang et al. [14] used a propane burner as an ignition source to comparatively investigate the combustion characteristics of single-glass and double-glass PV modules subjected to localized high-temperature exposure. It was revealed that single-glass modules exhibited markedly higher fire risk than double-glass modules. Single-glass modules were more susceptible to burn-through by flame torches, exhibiting faster ignition, broader surface flame spread, and a higher heat release rate. Ju et al. [15] employed a flame torch to study the re-radiation from PV module fires to a roof and the evolution of backsheet flame morphology under different inclination angles. It was demonstrated that, as the module inclination angle increased, the radiative feedback from the PV fire to the roof surface decreased, and both the extension length and vertical thickness of the backsheet flames were reduced. Cancelliere et al. [16] investigated the arc generation characteristics of PV modules exposed to an external fire source and observed that series, parallel, and ground arc faults may occur during flame spread. These high-temperature arcs could further act as ignition sources and promote fire development. In addition, the elevated temperatures associated with arcing were shown to compromise the stability of the frame structures, while the induced temperature gradients may also lead to fracture of the tempered glass used in PV modules. Lin et al. [17] employed a propane burner to simulate a steady pool fire acting on adjacent inclined PV panels within an array and analyzed the flame shape and attachment characteristics of the burner flame in the presence of inclined PV surfaces. It was observed that air entrainment induced by the PV modules caused the flame inclination angle to initially increase and then decrease as the module inclination angle was further increased. Manzini et al. [18] reviewed various test standards for assessing the fire performance of PV modules and showed that current European standards had notable limitations, particularly the lack of explicit consideration of module inclination.

These standards typically used gas burners to evaluate combustion performance, and comparative experiments had demonstrated that when the ignition source was located beneath the module, PV modules installed at an inclination suffered more severe fire damage. As revealed in previous studies, most experimental investigations had relied on gas burners to reproduce the localized overheating in PV modules caused by direct current arc faults or hotspot faults. However, this type of ignition setup differed markedly from real fire scenarios in terms of flame coverage and heat flux, leading to fire characteristics that deviated from actual conditions and making it difficult to realistically capture the impact of external fire sources on PV modules, such as wildfires or rooftop fires.

Furthermore, several researchers have focused on failure patterns related to glass breakage of PV modules. Wang et al. [19] combined a uniform radiant panel and a finite element model (FEM) to investigate the cracking time and thermal stress distribution characteristics of PV modules with different inclination angles. It was found that as the temperature continues to rise, the glass of PV modules could exceed their thermal stress tolerance, leading to cracked initiation or even complete fracture. Moreover, when the inclination angle of PV modules exceeded 30°, the cracked generation rate of the glass panels decreased significantly. Dong et al. [20] conducted comparative experiments to analyze the cracked morphology of the glass panels and glass detachment ratio of different types of PV modules. It was shown that the temperature-rise rate and glass detachment ratio of non-hollow PV modules were much higher than those of hollow PV modules. Ju et al. [17] performed small-scale combustion experiments on single-glass PV modules via a cone calorimeter. It was observed that flammable gas bubbles emerged between the glass and crystalline silicon layers during the PV module burning process. Further results demonstrated that the modules' heat release rates increased subsequent to glass fracture, as combustible components within the encapsulation materials were exposed to atmospheric oxygen. Akram [21] identified through a comprehensive literature review that glass fracture occurred in PV modules subjected to long-term outdoor service, which impaired the reliability of the modules. An analysis of the aforementioned literature revealed that previous studies have demonstrated that during fire scenarios, PV modules were prone to surface glass fracture due to uneven thermal stress distribution. Additionally, the combustion characteristics and surface temperature distribution of the modules were notably altered post-fracture. However, there was a paucity of systematic experimental research on the fire behavior of PV modules exhibiting pre-existing glass fracture prior to ignition.

To fill this knowledge gap, this study intended to conduct fire experiments on single-glass PV modules using a pool fire as the external fire source, aiming to investigate the fire characteristics of both intact and cracked PV modules. It focused on analyzing the burning process of the PV module fire under different inclination angles, the temperature-rise characteristics of the modules, and the combustion behaviors of the molten dripping flames. Furthermore, this study aspired to elucidate the differences in fire behavior between intact and cracked PV modules and comprehensively elaborated on the damage characteristics of PV modules exposed to external fire sources. It ultimately provided theoretical references and data support for fire protection design and fire risk assessment for PV power generation systems.

2. Experimental Setup

Figure 1a presents a schematic diagram of the experimental platform, which is composed of single-glass PV modules, a fuel pool, fireproof fabric, thermocouples, CCD cameras, an infrared camera, and an adjustable PV module bracket. All experiments were performed in a semi-enclosed test facility to mitigate interference from ambient wind.

Single-glass PV modules with dimensions of 1640×992 mm were selected as the research objects for the experiments. The multi-layer structure of the single-glass PV modules and the key parameters of each component are illustrated in Figure 1d. From the front side to the back side, the module consisted of the following layers in sequence: tempered glass, Ethylene Vinyl Acetate (EVA) adhesive film, a crystalline silicon cell, EVA adhesive film, and a Tedlar film–polyethylene terephthalate–Tedlar (TPT) film backsheet. In this study, the test specimens consisted of single-glass PV modules with two conditions: intact tempered glass and locally cracked tempered glass. The locally cracked modules were produced using a force-controlled impact hammer. Details of the cracked modules and the cracked locations are shown in Figure 1f,g. These locally cracked tempered glass PV modules were designed to simulate two typical failure scenarios, specifically glass cracking arising from overheating due to equipment malfunctions and glass fracture resulting from PV module aging during long-term outdoor service. A series of comparative experiments was conducted to systematically investigate the fire behavior of the modules under the external pool fire. Five inclination angles (0° , 15° , 30° , 45° , and 60°) were considered for both intact and cracked PV modules, resulting in ten distinct test configurations, as summarized in Table 1. Each configuration was tested at least twice to ensure the repeatability and reliability of the results.

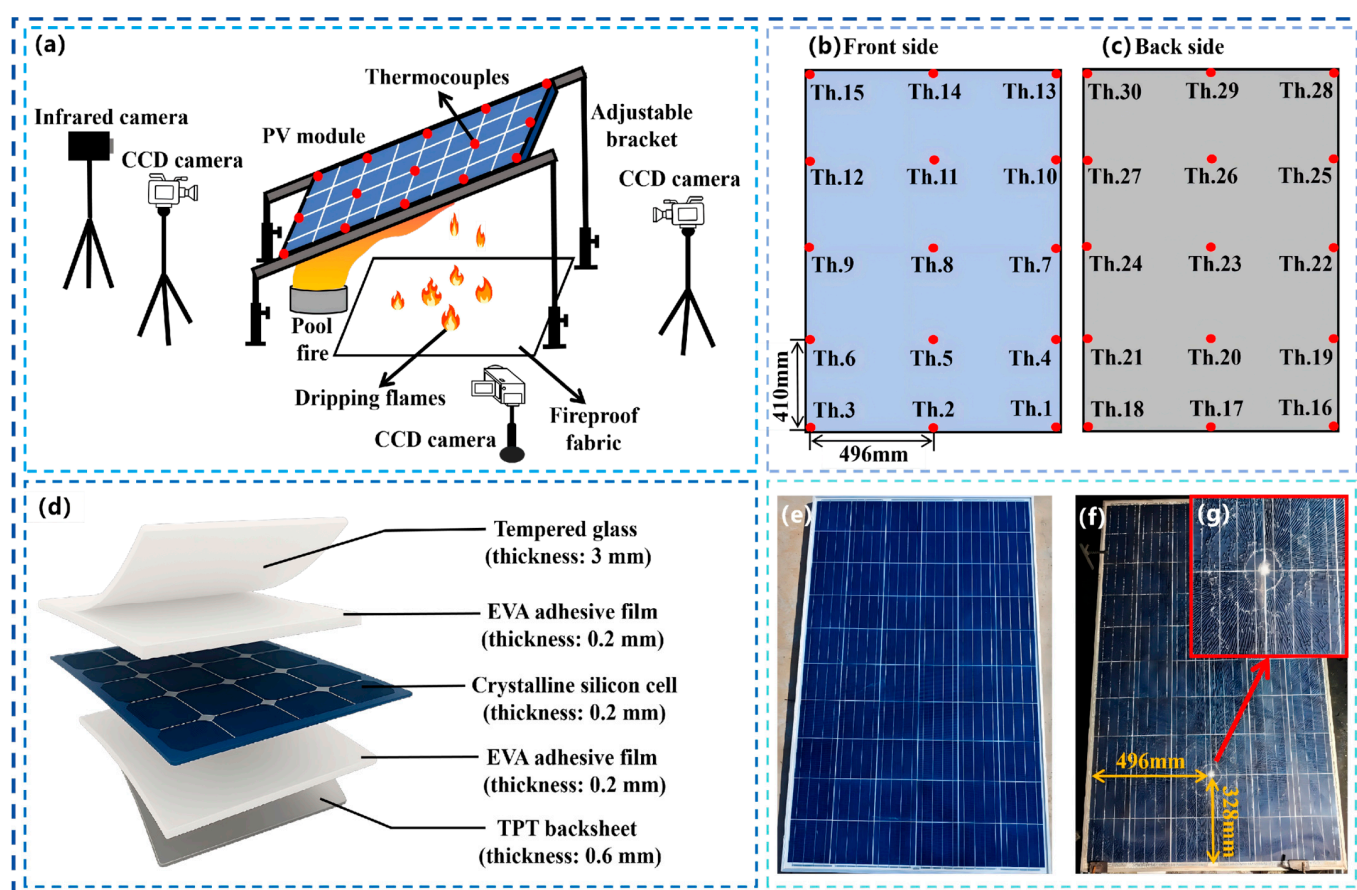


Figure 1. (a) Schematic diagram of the experimental platform. (b) Measurement locations on the front side of the PV module. (c) Measurement locations on the back side. (d) Schematic diagram of the PV module structure. (e) Intact PV module. (f) Cracked PV module. (g) Partial magnified section of the cracked module.

Table 1. Specification of the test conditions.

Test No.	Inclination Angle (°)	Integrity Condition	Test No.	Inclination Angle (°)	Integrity Condition
1	0	Intact	6	0	Localized, cracked
2	15	Intact	7	15	Localized, cracked
3	30	Intact	8	30	Localized, cracked
4	45	Intact	9	45	Localized, cracked
5	60	Intact	10	60	Localized, cracked

The experiment utilized a circular steel fuel pool with a diameter of 37.5 cm and a sidewall height of 12.5 cm, positioned 20 cm directly beneath the junction box of the PV module. The fuel used in the experiments was gasoline (92 octane), with an initial fuel mass of 2.75 kg. Prior to the formal experiments, the steady-state combustion rate of the pool fire measured using a high-precision electronic balance was 2.87 g/s. A fireproof fabric sheet with dimensions of 1500 mm × 1200 mm was placed beneath the PV module to facilitate observation of the molten dripping flames during the experiments.

A series of K-type thermocouples (diameter: 1 mm; uncertainty: 0.1 °C) were fixed to the front and back surfaces of the experimental samples to collect real-time temperature data, and their placement is shown in Figure 1b,c. During the experiments, three CCD cameras were deployed and positioned at the front, side, and back of the PV module to record the surface damage of the module, the molten dripping flames, and the flame attachment on the backsheet. In addition, an infrared camera (measurement range: 0–1200 °C; uncertainty: 0.1 °C; frequency: 50 Hz) was used to capture the transient surface temperature distribution of the PV module throughout the experiments.

3. Results and Discussion

3.1. Burning Process

Figure 2 illustrates the front and side views, as well as infrared thermal images, of an intact PV module at a 30° inclination angle under a representative test condition (Test No. 3), all captured at the same time instants. As demonstrated in Figure 2a, the height of the pool fire increased rapidly, with its flame spreading along the backsheet of the PV module after ignition. Under the radiative heating of the fire plume, a grayish blistering region appeared on the module surface directly above the pool fire. As the pool fire continued to burn, this grayish region progressively expanded, and the crystalline silicon cells located above the fire began to crack and spall off. Meanwhile, the side view in Figure 2b shows that the burn damage of the PV module was accompanied by dripping of molten droplets, and these molten dripping flames continued to burn for a period after reaching the fireproof fabric. Once the silicon cells had fragmented, the tempered glass was directly exposed to the flame. At this stage, both the dripping frequency and the burning duration of the molten dripping flames began to decrease. Eventually, as the pool fire was gradually extinguished, the degree of burning damage to the PV modules ceased to expand, the dripping phenomenon stopped, and the molten dripping flames on the fireproof fabric gradually faded away, with no sustained combustion observed. Details of the burning process are provided in the Supplementary Materials.

Figure 2c shows the temperature distribution on the front surface of the intact PV module at the corresponding moment. It can be clearly observed from the figure that after exposure to the pool fire, the front surface of the intact PV module exhibited a rapid temperature rise, with a notable temperature gradient formed on its surface. As the pool fire persisted in burning, the overall temperature of the module's front surface rose slowly, the high-temperature zone continued to expand, and the temperature in the areas where crystalline silicon cells had detached was significantly higher than that in the areas

where they remained attached. Eventually, the pool fire gradually diminished and was extinguished, and the overall surface temperature of the PV module gradually decreased.

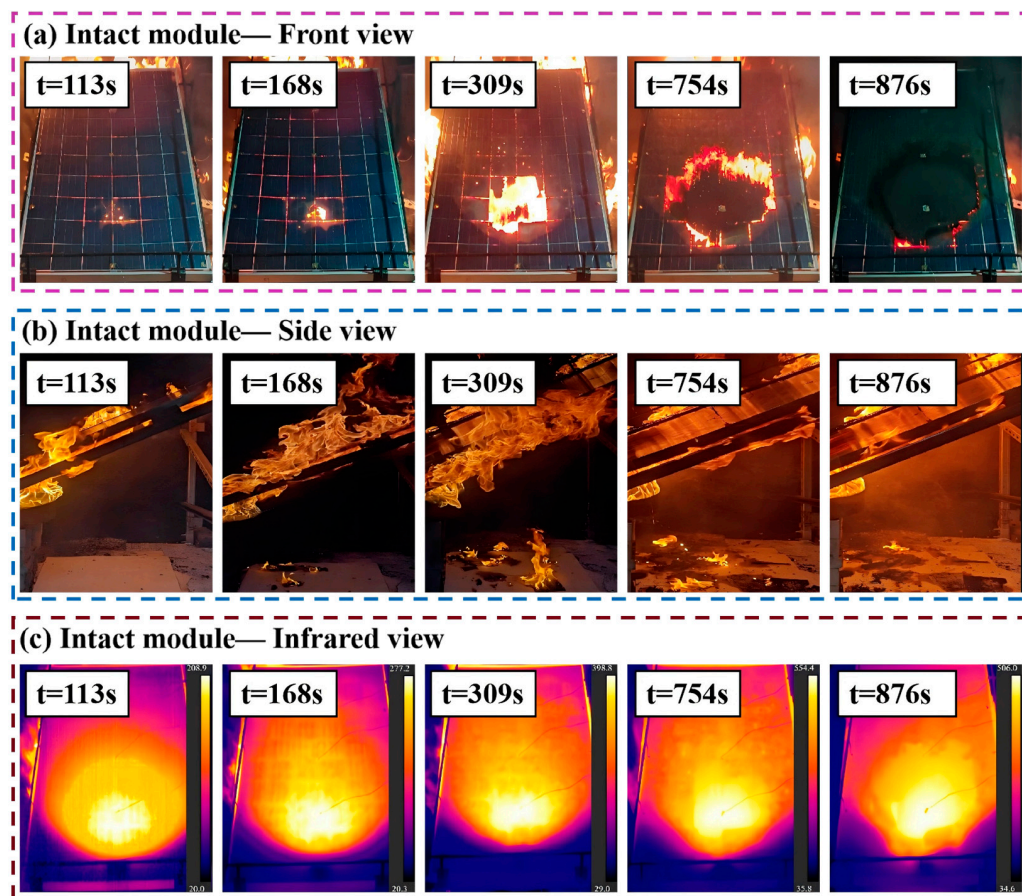


Figure 2. Typical experimental snapshots of the burning process of intact modules at different times.

Figure 3 presents a flame morphology diagram and schematic of the flame-affected zone on the backsheet. It can be distinctly observed that the external flame beneath the PV module could not fully cover its backsheet. Based on the flame coverage on the PV module backsheet under different inclination angles, the PV module could be divided into three zones: the flame-unaffected zone, the continuous heating zone, and the intermittent heating zone, as illustrated in Figure 3c. Combined with the systematic analysis depicted in Figure 2, there existed distinct differences in the temperature-rise characteristics and burning behaviors across the three zones of the PV module. The temperature of the flame-unaffected zone was significantly lower than that of the other zones, and no ignition of the TPT film backsheet was observed in this zone. The flame in the continuous heating zone remained stably attached to the PV module, exhibiting the highest temperature-rise rate and burning damage rate, thereby resulting in the most severe degradation of the module throughout the fire exposure period. The intermittent heating zone, affected by air entrainment, experienced intermittent contact between the pool fire plume and the TPT film backsheet, resulting in a lower temperature compared to that of the continuous heating zone. There was a direct correlation between the temperature characteristics, burning damage severity, and the flame contact conditions.

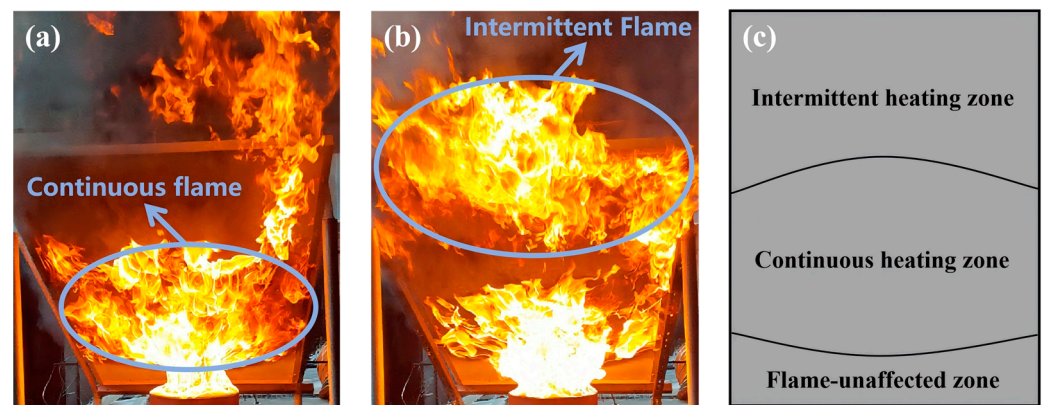


Figure 3. Flame morphology diagram of the back side: (a) continuous flame; (b) intermittent flame; (c) schematic of the flame-affected zones.

To clarify the differences between intact and cracked modules under the pool fire, Figure 4 presents the front view, side view, and simultaneous infrared images of the cracked module at a 30° inclination angle under the corresponding condition (Test No. 8). Compared to intact PV modules, the burning process of the cracked modules was significantly faster. The backsheet of the cracked module initiated the rapid generation of molten dripping flames, which mostly demonstrated spontaneous self-extinction during their descent. Subsequently, longitudinal surface fissures propagated across the cracked PV module, with flames and copious quantities of gas issuing from the fissures. Concurrently, the backsheet sustainably generated molten dripping flames that sustained combustion over a brief duration upon dripping onto the ground. As the pool fire continued to burn, the flames penetrated the longitudinal surface fissures, accompanied by the generation of a substantial amount of molten dripping flames that combusted persistently upon contacting the ground. Under sustained exposure to the external fire source, extensive detachment was observed on the cracked module. The pool fire directly penetrated the module rather than propagating along its backsheet, with the delaminated components persisting in combustion on the fireproof fabric placed beneath the module. Ultimately, the pool fire diminished progressively, with sustained stable flames occurring at the edges of the module burn-through zones. Concurrently, the dripping frequency and combustion duration of the molten dripping flames exhibited a gradual reduction.

Figure 4b presents the surface temperature distribution characteristics of the cracked module. It could be distinctly observed that the cracked module underwent a rapid temperature rise upon exposure to the pool fire, with its temperature at corresponding time points being significantly higher than that of the intact module. Subsequently, the high-temperature zone was penetrated by the pool fire, and fissures propagated around the burn-through zone, with high-temperature flames issuing from both the burn-through zone and the fissures. With the pool fire continuing to burn, the cracked module experienced extensive fragmentation and spalling across its structure. The pool fire directly penetrated burn-through zones, thereby compromising the heat transfer capability of the module and resulting in a diminished spatial extent of the surface high-temperature zone. Ultimately, as the pool fire progressively diminished, the high-temperature zone on the module surface experienced continuous contraction, and the surface temperature exhibited a gradual reduction, while the temperature at the edges of the burn-through zone maintained a relatively heightened level.

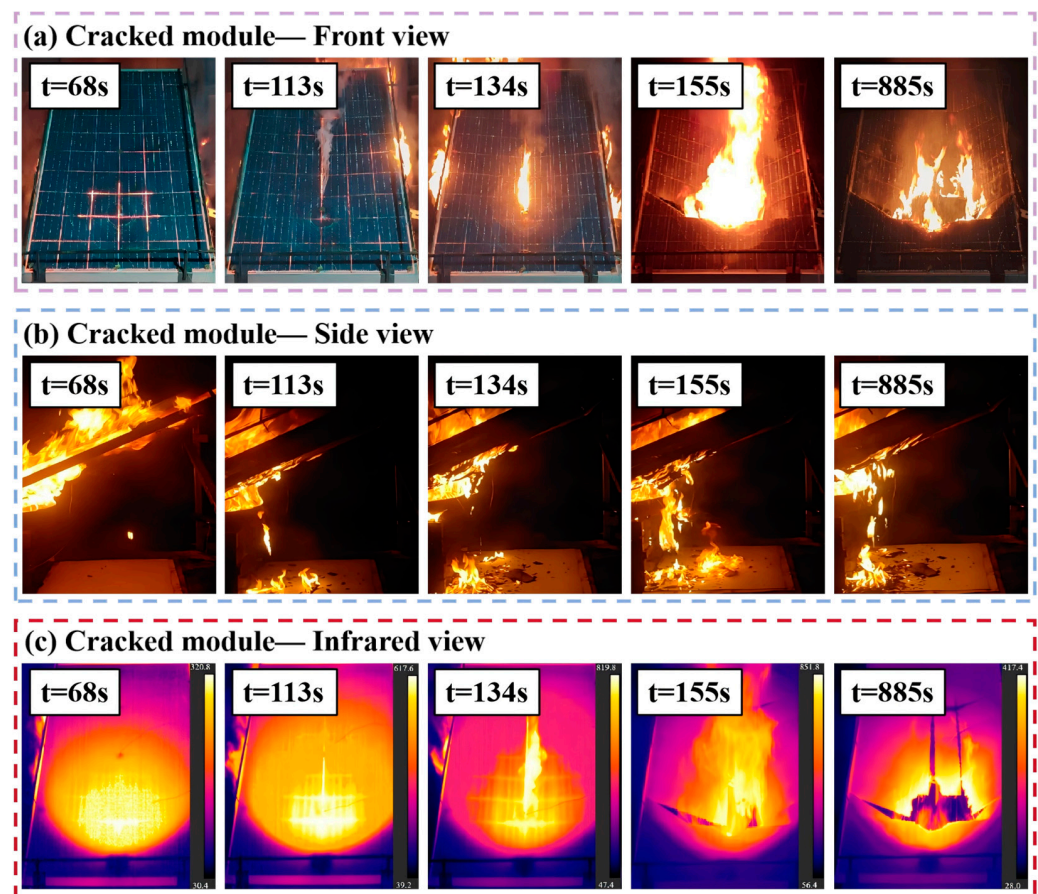


Figure 4. Typical experimental snapshots of the burning process of cracked modules at different times.

As can be inferred from the preceding descriptions, the burning process of intact modules was relatively sluggish with a lower overall surface temperature. Conversely, the cracked module exhibited an accelerated burning process and was therefore susceptible to rapid penetration by the pool fire. Meanwhile, both the continuous dripping duration and the combustion time of the molten dripping flames of the cracked modules were significantly longer than those of the intact PV modules. This phenomenon indicated that the integrity of the front glass was a critical factor determining the fire resistance of the PV modules.

3.2. Temperature Characteristics

During the burning process, the temperature fields of both the front glass and backsheet of the PV modules demonstrated a non-uniform distribution, with a pronounced temperature gradient. Figure 5 presents the temperature variation curves for ten temperature measurement locations along the central axis of the module's front surface and backsheet, using Test 3 (30°, intact) and Test 8 (30°, cracked) as representative cases.

Figure 5b illustrates that under pool fire exposure, the temperatures of five measurement points on the front surface of the intact module first rose rapidly, followed by a more gradual increase, and ultimately decreased as the pool fire weakened and was extinguished. Among these points, Th.5—located directly above the fire source and closest to the pool fire—exhibited the fastest temperature rise, with a peak temperature of 537.4 °C, which was 1.55 times that of the peak temperature at Th.8. This was primarily attributed to the fact that Th.8 was farther from the external fire source and thus subjected to a lower incident radiative heat flux. As the distance from the fuel pool center increased, the temperature-rise rates at Th.11 and Th.14 decreased further. Notably, before the pool fire was extinguished,

the temperature at Th.2 (near the module bottom) increased almost linearly at a nearly constant rate, reaching a maximum of only 84.6 °C—markedly lower than those recorded at the other thermocouples. Furthermore, as the external fire steadily subsided and was fully extinguished, the temperatures at the other locations exhibited noticeable fluctuations, whereas the temperature at Th.2 displayed significantly smoother variations. This behavior stemmed from the observation that, under the tested conditions, most of the backsheet was directly engulfed by the pool fire, while the region surrounding Th.2 did not come into direct contact with the flame. Consequently, the temperature rise at Th.2 was dominated by heat conduction within the PV module.

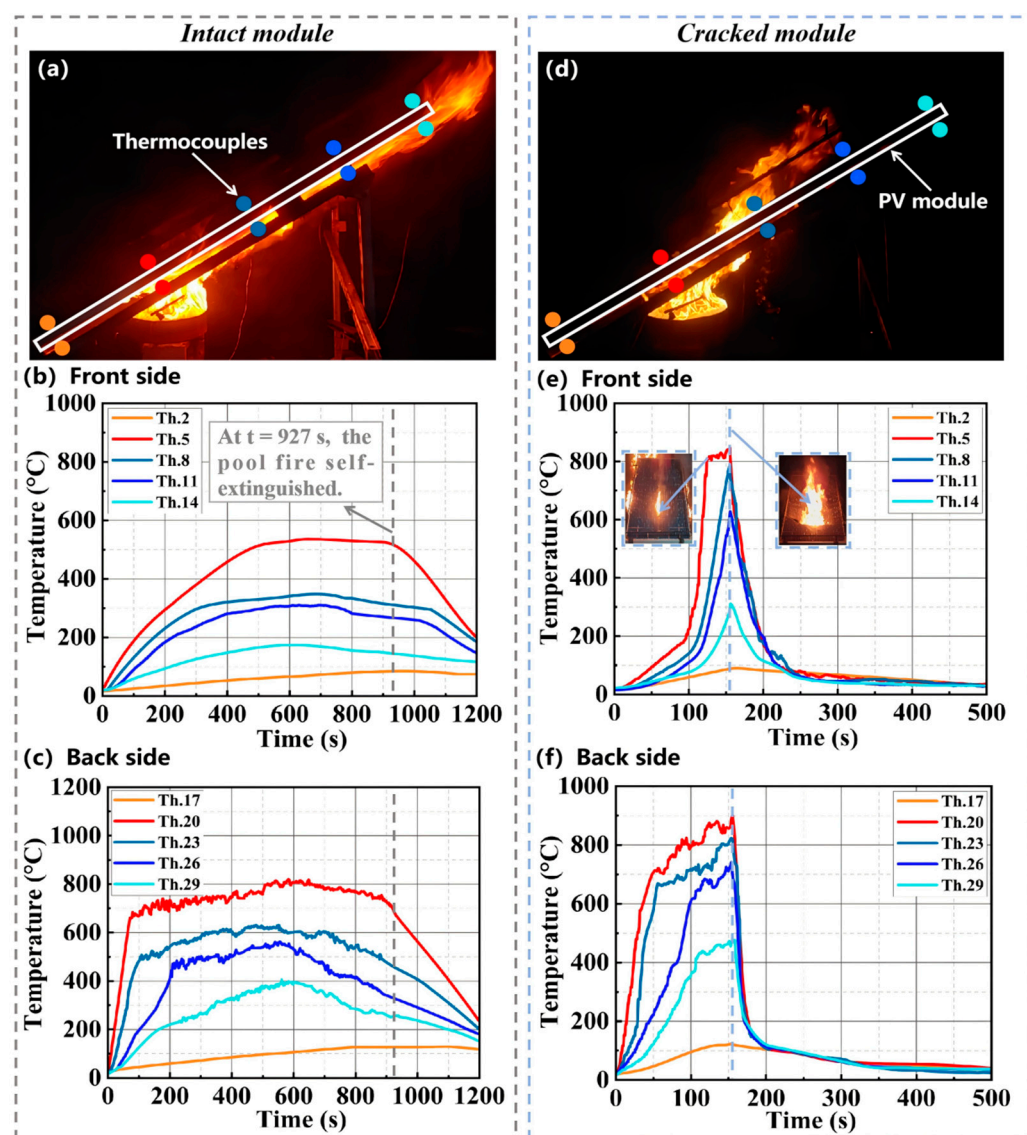


Figure 5. Lateral flame morphologies and temperature profiles of PV modules at 30° inclination: (a) lateral flame configuration of the intact module; (b) temperature profile on the front side of the intact module; (c) temperature profile on the back side of the intact module; (d) lateral flame configuration of the cracked module; (e) temperature profile on the front side of the cracked module; (f) temperature profile on the back side of the cracked module.

As shown in Figure 5c, both the temperature-rise rates and peak temperatures at the corresponding points on the backsheet of the intact module were significantly higher than those on the front surface. For example, the maximum temperature at Th.20, which was located directly above the fire source on the backsheet, reached 813.5 °C. In contrast, the

peak temperature at the corresponding front-surface point Th.5 was only 66% of this value. At the bottom of the module, Th.17, which was not directly in contact with the pool fire, maintained a relatively low temperature and exhibited an almost linear increase similar to that of the front-surface point Th.2, but its temperature was still markedly higher than that at Th.2. This was mainly because the pool fire directly heated the back surface of the PV module, and the multilayer laminated polymer composition of the PV module behaved as a thermally thick material, so that heat transfer to the front surface required a finite time [22]. In addition, the backsheet temperature was influenced by the comprehensive effects of the external fire and combustion of the encapsulated polymer materials, leading to small-amplitude oscillations in the temperature curves.

Overall, a combined analysis of the front-side and back-side temperature trend indicated a strong correlation between the temperature-rise characteristics at the corresponding positions, while zones subjected to different flame-attachment conditions exhibited distinctly different temperature tendencies. This observation was consistent with the exponential temperature decay model proposed by Liu [23]. As the distance from the fire source increased, the temperature of the photovoltaic modules followed a clear exponential decay pattern. This behavior suggested that the rate of temperature decrease accelerated with distance, thereby confirming the consistent pattern of heat transfer and temperature decay under inclined fire source conditions.

Figure 5e,f present the temperature histories along the centerline of the cracked PV module. Under pool fire exposure, the temperature of the cracked module rose sharply. At $t = 134$ s, the external fire source burned through the module, and the flame penetrated the vertical crack, causing the temperature at Th.5 to surge rapidly to 809.2 °C. By $t = 155$ s, large-scale fracture and spalling of the module occurred, and the temperatures at the front-side measurement points reached their respective maximum values. Subsequently, the external flames broke through the burn-through zones rather than continuously impinging on the backsheet, resulting in a steep decline in the module temperature. Meanwhile, the temperatures of the back side at various locations also plummeted abruptly after attaining their peak values, with a pronounced temperature gradient evident between thermocouples at the centerline.

Compared with the intact module, both the temperature-rise rates and peak temperatures at the measuring points of the cracked module were significantly higher, indicating a more intense thermal response. This was mainly because cracks in the front glass of the cracked module facilitate air ingress into the encapsulation layers, thereby accelerating the heating of the EVA encapsulant to its ignition conditions and promoting more vigorous combustion.

Based on the above analysis, the temperature-rise characteristics of single-glass PV modules exhibited distinct spatial variations across different locations. To further quantify the temperature-rise rates in different flame contact zones, a CCD camera deployed behind the PV module was used to record the flame contact area on the PV module during the steady burning stage, and the video data were post-processed in MATLAB 2023 to divide the module into different flame-affected zones according to the definitions given in Section 3.1. Subsequently, in combination with the temperature data from the measurement points within each region and using Equation (1), the average temperature-rise rates of the front and back surfaces were calculated for each region, thus facilitating the precise quantification of region-specific thermal response under different inclination angles and front-glass integrity conditions.

$$\varphi = \frac{\sum_{i=1}^n \frac{T_{i,\alpha} - T_{i,0}}{\Delta t_i}}{n} \quad (1)$$

where φ represents the average temperature-rise rate, °C/s; $T_{i,n}$ and $T_{i,0}$ refer to the maximum and initial temperatures at the measurement point respectively, °C; Δt_i represents the time from ignition of the external fire source to the moment when the temperature at the measurement point i reaches peak value (s); and n represents the number of measurement points within the zone.

Figure 6a presents the average temperature-rise rates of the different regions on the front surface of the intact PV modules at various inclination angles. In general, the continuous heating zones consistently exhibited much higher average temperature-rise rates than the other regions, whereas the flame-unaffected zones exhibited the lowest average temperature-rise rates, indicating that stable flame attachment and prolonged heating dominated the rapid temperature increase in the PV module. As the inclination angle increased from 0° to 60°, the average temperature-rise rates in all regions displayed a non-monotonic trend of first increasing and then decreasing, reaching their maxima at an inclination angle of 15°. When the inclination angle was set to 0°, the average temperature-rise rates in the flame-unaffected zone and the intermittent heating zone were only 0.05 °C/s and 0.16 °C/s respectively, which were significantly lower than those at the other inclination angles. This behavior can be primarily attributed to the fact that horizontal installation markedly modified the flame morphology and the associated air entrainment pattern. Under this configuration, the flame plume impinged on the underside of the module and transitioned into a ceiling jet flow that propagated laterally beneath the backsheet, rather than spreading along the panel. A similar phenomenon was also reported by Kristensen in a study of flame spread in rooftop PV fires [24]. As a result, the effective flame-affected zone and the duration of sustained flame attachment were reduced. The weakened convective and radiative heating consequently limited the expansion of pyrolysis in the encapsulation materials, delayed the development of continuous flaming, and ultimately suppressed the temperature-rise rates observed across monitored zones. This interpretation was consistent with a prior PV fire study, which indicated that changes in flame attachment and entrainment asymmetry can significantly regulate heat transfer and thermal response [23].

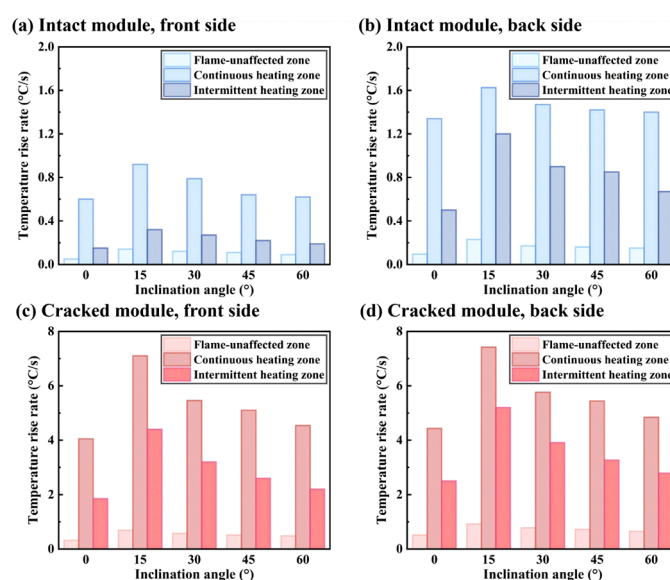


Figure 6. Average temperature-rise rates of different zones: (a) intact module, front side; (b) intact module, back side; (c) cracked module, front side; (d) cracked module, back side.

When the inclination angle was increased to 15°, the average temperature-rise rates of the continuous heating zones and the intermittent heating zones respectively rose to

0.92 °C/s and 0.33 °C/s, corresponding to percentage increases of 53.33% and 106.25% relative to the 0° inclination angle. This enhancement stemmed from the observation that a moderate increment in the inclination of the PV module mitigated the impedance to air entrainment imposed by the module itself, thereby facilitating enhanced heat transfer from the pool fire to the PV module [25]. With a further increase in inclination to 60°, the average temperature-rise rates across all zones exhibited a subsequent decline. This phenomenon was primarily attributed to the synergistic effects of flame attachment behavior and the module-induced restriction of air entrainment [17], which collectively reduced both the lateral spread and vertical thickness of the flame plume, diminished the local external heat flux incident on the module, and ultimately resulted in a continuous decrease in the regional average temperature-rise rates.

Figure 6b shows that, as the inclination angle of the PV module increased from 0° to 60°, the average temperature-rise rates in the various zones on the backsheet of the intact module first increased rapidly and then gradually decreased. This trend was generally consistent with that observed on the front surface, but the values were systematically higher than those of the corresponding zones on the front side. For example, at an inclination angle of 45°, the average temperature-rise rate in the intermittently heated zone on the back surface was 0.85 °C/s, which was approximately 3.86 times that of the corresponding zone on the front surface, further confirming the thermally thick characteristics of single-glass PV modules. Specifically, the pronounced discrepancy indicated that the heat imposed by external fire was not conducted through the module rapidly enough to eliminate the through-thickness temperature gradient. Consequently, a substantial through-thickness temperature gradient persisted, such that the backsheet exhibited a markedly stronger and faster thermal response than the front side under the same fire exposure conditions.

Figure 6c,d demonstrate the average temperature-rise rates of the different zones of the cracked modules. It was evident from the results that, with increasing inclination angle, the front and back surfaces of the cracked module exhibited the consistent evolutionary trend that characterized the intact module. However, for the same inclination angle, the average temperature-rise rates of the cracked module were markedly higher than those of the intact module, indicating a much more rapid heating process. For instance, at an inclination angle of 60°, the average temperature-rise rate in the intermittent heating zone on the front side of the cracked module reached 2.2 °C/s, which was 11.58 times that of the corresponding zone on the intact module. The temperature-rise rates in all zones on both sides of the cracked module were substantially higher than those in intact counterparts, thus exhibiting a markedly more rapid heating process. This pronounced enhancement was attributed to the presence of cracks in the tempered glass, which substantially degraded its fire resistance and allowed external air to more readily penetrate the encapsulation layer, thereby facilitating the attainment of ignition conditions and promoting more vigorous combustion.

The above analysis demonstrated that single-glass PV modules exhibited pronounced spatial variations in temperature-rise rates across both front and back surfaces under varying glass integrity conditions. The continuous heating zone consistently showed the highest temperature-rise rate. In contrast, the flame-unaffected zone displayed the lowest rate, with this phenomenon underscoring that stable flame attachment and prolonged thermal exposure were the dominant contributors to the rapid temperature elevation. As the inclination angle increased from 0° to 60°, the average temperature-rise rates of all zones displayed a non-monotonic variation trend, first increasing and then decreasing.

3.3. Comprehensive Analysis of the Fire Characteristics of PV Modules

A more intuitive and comprehensive characterization of PV fire behavior is achieved by systematically comparing the influence of the glass integrity on the burning process of single-glass PV modules at different inclination angles, utilizing six fire characteristic parameters: maximum temperature-rise rate on the front surface (v_1 , °C/s); maximum temperature-rise rate on the backsheet (v_2 , °C/s); burn-through rate (p , cm²/s); dripping frequency of molten droplets (f_{drip} , s⁻¹); expansion rate of the pyrolysis zone (ϕ_{pyro} , cm²/s); and average combustion duration of molten dripping flames (t_{drip} , s). Among these parameters, v_1 and v_2 are obtained from Equation (2), p is obtained from Equation (3), f_{drip} is obtained from Equation (4), and ϕ_{pyro} is obtained from Equation (5). The parameter t_{drip} represents the average time elapsed from the moment a molten dripping flame first contacts the ground until its flame is completely extinguished.

To quantitatively compare the temperature-rise rates on the front and back surfaces of the PV module, the thermocouple data were processed using Equation (2) to obtain the maximum temperature-rise rates on the front and back surfaces, denoted by v_1 and v_2 respectively.

$$v = \max_i \left(\frac{T_{i,\alpha} - T_{i,0}}{\Delta t} \right) \quad (2)$$

where v denotes the maximum temperature-rise rate on either the front or back surface (°C/s), $T_{i,\alpha}$ and $T_{i,0}$ represent the peak and initial temperatures at measurement point i respectively (°C), Δt_i refers to the time elapsed from ignition of the pool fire to the instant when the temperature at measurement point i reaches its peak value (s).

Under external fire exposure, cracked modules are burned through within a relatively short time. To quantify the effect of the module inclination angle on the burning process, a burn-through rate, p , was defined, calculated as the ratio of the burn-through area of the PV module to the time required for being burned through.

$$p = \frac{A_\alpha}{t_\alpha} \quad (3)$$

where p denotes the burn-through rate (cm²/s), A_α represents the area of the burn-through zone of the module (cm²), and t_α is the time required for the occurrence of the large-area detachment of the module (s).

To quantify the dripping characteristics of the PV module, the dripping frequency of molten droplets, f_{drip} , was calculated using Equation (4). This parameter reflects the activity level of the dripping behaviour and is thus employed to evaluate the potential of PV modules to generate secondary ignition sources under external fire exposure.

$$f_{drip} = \frac{n}{t_e} \quad (4)$$

where f_{drip} denotes the dripping frequency (s⁻¹), n represents the total number of molten dripping flames during the experiments, and t_e refers to the total burning duration of the pool fire (s).

Thermal infrared video data were processed using MATLAB 2023. Given that the minimum temperature at which the EVA encapsulant in PV modules starts to generate pyrolysis gases is 320 °C [26], this temperature was adopted as the threshold for defining the pyrolysis zone. Accordingly, areas of the module with temperatures above 320 °C were identified as pyrolyzing zones. On this basis, the expansion rate of the pyrolysis zone,

ϕ_{pyro} , was calculated from Equation (5) to quantify the pyrolysis behavior of PV modules under external fire exposure.

$$\phi_{pyro} = \frac{A_{pyro}}{t_0} \quad (5)$$

where ϕ_{pyro} represents the expansion rate of the pyrolysis zone (cm^2/s), A_{pyro} denotes the maximum area of the pyrolysis zone over the entire burning process (cm^2), and t_0 refers to the time required for the high-temperature region on the PV module to develop from its initial appearance to its maximum extent (s).

Figure 7 illustrates comparative radar plots of six fire characteristic parameters for intact and cracked PV modules across varying inclination angles. A comparison of the intact modules in Figure 7a shows that the inclination angle has a pronounced influence on the fire behaviour of the PV modules. Under external flame exposure, the module installed at an inclination of 15° exhibits generally higher values for all parameters, indicating that the comprehensive fire risk at this angle is greater than at the other inclination angles. In contrast, the horizontally mounted module (0°) shows consistently lower values for all indicators and thus a comparatively lower fire risk. Consistent with the temperature-rise behavior observed across different zones, the fire characteristic parameters also exhibit a non-monotonic variation trend with varying inclination angle.

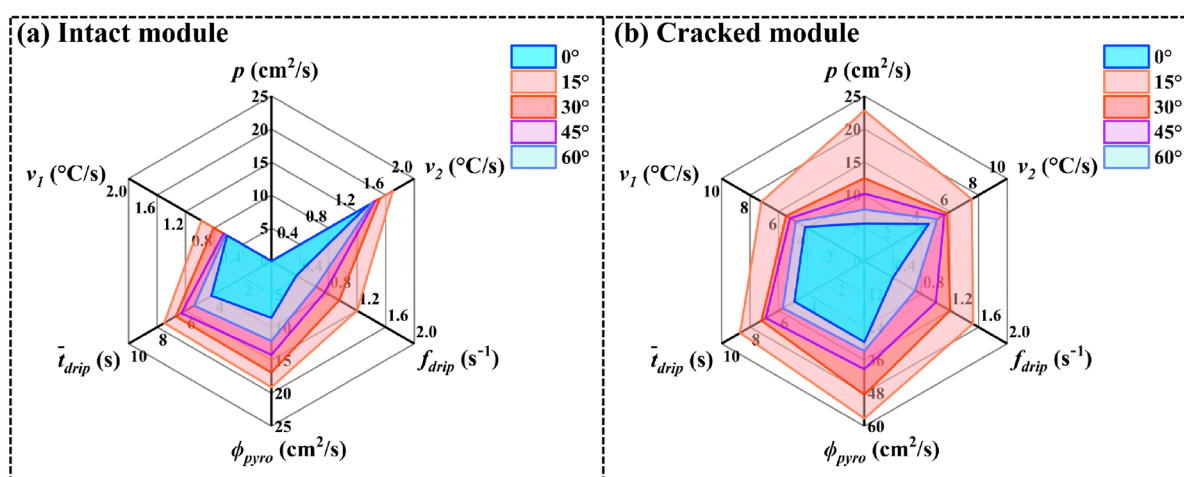


Figure 7. Comprehensive analysis of the fire characteristics of PV modules.

Compared with the intact modules, the cracked modules exhibit a markedly higher fire hazard at all inclination angles. For any given inclination angle, the six fire characteristic parameters are consistently higher for cracked modules, indicating a marked overall increase in fire intensity and associated risk. For example, at an inclination angle of 15° , the values of v_1 and v_2 of the cracked modules are significantly higher than those for the intact modules, while p and ϕ_{pyro} also increase simultaneously, reflecting faster heating, more rapid pyrolysis development and a stronger tendency toward structural failure. At the same time, both f_{drip} and $\bar{t}_{drip}$ consistently attain the maximum values among all inclination angles, implying that molten dripping flames not only occur more frequently but also feature an extended combustion duration, thereby enhancing the probability of igniting adjacent combustibles. It is noteworthy that v_1 , v_2 , p , ϕ_{pyro} , f_{drip} and $\bar{t}_{drip}$ exhibit positive correlations. As the temperature rise rates of the PV modules increase, the fire characteristic parameters p , ϕ_{pyro} , f_{drip} and $\bar{t}_{drip}$ all exhibit a corresponding elevation. This demonstrates that rapid temperature rise, pyrolysis, burn-through, and molten droplet formation during the burning process are not independent phenomena, but rather interrelated and synergistic in their development. Faster temperature-rise rates

accelerate the evolution of pyrolysis behavior, promote more extensive burn-through, and result in more frequent molten dripping flames with longer combustion durations. The strong positive correlations among these fire characteristics further demonstrate that, under external fire exposure, the heating, pyrolysis, burn-through and dripping behaviour of PV modules are governed by an intrinsically coupled mechanism.

Fundamentally, these differences stem from the presence of cracks in the tempered glass of cracked modules, which compromises both the fire resistance and oxygen blocking capability for the multi-layered encapsulation materials. As a result, ambient air can more easily penetrate the EVA and other combustible encapsulation materials, thereby facilitating quicker attainment of ignition conditions and more vigorous combustion under external fire exposure. Consequently, cracked modules exhibit greater magnitude values, more rapid progression, and more pronounced responses across various fire characteristic indicators.

4. Conclusions

In this study, a series of fire experiments was conducted on single-glass PV modules at varying inclination angles under external fire exposure. The effects of installation inclination angle and front tempered glass integrity on the temperature response, burn-through behavior, and molten dripping flames of the modules were systematically investigated. Furthermore, by integrating thermocouple measurement, infrared video, and CCD imaging with multi-parameter analysis, several key fire characteristic parameters were quantitatively evaluated. The key findings of this study are as follows:

- (1) The integrity of the tempered glass has a decisive influence on the fire behavior of PV modules. At identical inclination angles, cracked modules exhibit faster burning processes, higher temperature-rise rates, and greater susceptibility to burn-through by external fire exposure, along with more numerous molten dripping flames with prolonged combustion durations. Accordingly, their key fire characteristic parameters are all significantly intensified compared to those of intact counterparts.
- (2) Under external fire exposure, the temperature response of PV modules exhibits significant spatial non-uniformity along with pronounced thermally thick characteristics. Based on the flame attachment characteristics and surface temperature distribution, the module can be divided into three characteristic zones: the flame-unaaffected zone, the continuous heating zone, and the intermittent heating zone. The continuous heating zone demonstrates the highest temperature-rise rate, while the flame-unaaffected zone displays the lowest—indicating that stable flame attachment and sustained heating are the dominant factors governing the rapid temperature rise. Furthermore, under all test conditions, the temperature-rise rates and peak temperatures in each zone of the backsheet are generally higher than those of the corresponding regions on the front side.
- (3) The effect of module inclination angle on various fire characteristic parameters is non-monotonic. For both intact and cracked PV modules, with the inclination angle increasing from 0° to 60°, the comprehensive fire damage displays a trend of initial rise followed by subsequent decline, with the peak occurring at 15°—indicating that this inclination angle poses the most severe integrated fire hazard among all experiments. Conversely, all fire characteristic parameters attain their minimum values at a 0° inclination, indicating minimal fire hazard.
- (4) Strong correlations exist among the various fire characteristic parameters. A more rapid temperature-rise rate in PV modules is accompanied by more extensive expansion of the pyrolysis zone, more severe burn-through, an increased frequency of molten droplets, and prolonged combustion durations of the droplets. Thus, these fire characteristic parameters are not independent phenomena but intrinsically coupled

processes that collectively and synergistically characterize the comprehensive fire damage of PV modules in a multi-parameter perspective.

This work translates the experimental insights into multi-parameter guidance for fire risk assessment and fire protection design of photovoltaic power plants. The observed data and trends provide a quantitative basis for engineering decisions: maintaining front-glass integrity—through robust material selection and regular inspection to prevent or promptly address cracking—can substantially enhance module fire resistance, thereby mitigating fire spread and overall damage.

In addition to optimizing energy yield, the installation inclination angle should be carefully evaluated from a fire safety perspective, as configurations around 15° were found to exacerbate integrated fire hazards, whereas 0° exhibited the lowest risk. This is particularly important in low-latitude regions, where the optimal solar incidence angle for maximizing energy yield overlaps with the high-risk fire inclination angle [27]. In these areas, it is recommended to avoid the 15° inclination angle and slightly adjust the installation angle to reduce fire risk. In mid-latitude regions, we also suggest increasing the tilt angle of the PV modules, sacrificing a small amount of energy efficiency in exchange for improved safety. For high-latitude regions, where the optimal angle tends to be steeper, prioritizing energy efficiency while reinforcing structural design to accommodate wind loads is recommended. This strategy overcomes the limitations of optimizing a single objective, achieving a scientific balance between installation angle and fire safety across different latitudes.

Overall, by elucidating the temperature characteristics under distinct flame contact conditions and the behavior of molten dripping flames, which have seldom been addressed in existing studies, this study advances the state of the art in PV fire behavior and offers actionable recommendations to improve the fire resilience of PV systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/fire9020062/s1>.

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