Experimental investigation on thermal and toxic gas hazards of typical photovoltaic modules in fire

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Abstract. Considering that distributed photovoltaic systems are increasingly used in commercial buildings and residential areas, the potential safety hazards caused by building fires or photovoltaic system fires are very prominent. Photovoltaic fires have different characteristics from ordinary fires and are more difficult to extinguish immediately. The photovoltaic system itself will become an additional heat load in a fire, and the safety impact of the toxic gas released by it in densely populated areas is also very important.Based on the fire calorimetry method, this paper conducts an experimental study on the thermal hazards and toxicity hazards of typical photovoltaic panels under fire. Under different external heat radiation, several important combustion characteristic parameters of customized photovoltaic samples were investigated, such as, heat release rate, mass loss rate, total heat of combustion, etc. The instantaneous concentration of several key toxic gases was tested, and the risk was quantitatively analyzed through the FED value recommended in ISO13344:2015.

1 Introduction

The photovoltaic panel of laminated glass panel is one of the most widely used photovoltaic installations. Especially in solar power stations and building facades and rooftop solar systems.

For photovoltaic power station, once a large area of photovoltaic panel fire, the safety impact can not be ignored [1]. Especially for the building facade and roof, large-scale photovoltaic panels are attached to the building facade. Once the fire spreads vertically, the flammability of photovoltaic panels will cause great harm to the building safety [2]. At the same time, the toxic gases produced by the combustion of polymers in photovoltaic panels will cause great potential safety hazards in densely populated areas. In this paper, the combustion characteristics and combustion gas hazards of glass laminated polysilicon photovoltaic panels, which are widely used at present, are investigated experimentally.

2 Experimental setup

In order to match the size of the experimental sample with the test bench, in the experiment, a photovoltaic panel with a size of 18cm*18cm*0.35cm was ordered (Figure 1). The quality distribution of the sample mainly comes from factory database, as shown in table 1. The experimental platform comes from the Early Fire Characteristics Laboratory of the State Key Laboratory

of Fire, University of Science and Technology of China. Four thermal radiation powers were adopted to study the combustion characteristics and the effects of toxic gases, 15 KW/m², 20 KW/m², 30 KW/m², 40 KW/m².

Table 1. component dimensions and mass

	Glass panel	EVA	Polysilicon sheet	ТРТ
Length/cm	18	18	15.6	18
Width/cm	18	18	15.6	18
Thickness/mm	3	0.5*2	0.2	0.3
Substance mass/g	244.4	24.6	12.35	13.62



Figure 1. Schematic diagram of photovoltaic panel structure

3 Analysis and Result

3.1 Burning phenomenon

In practice, the direct effect of thermal radiation on the backplane of the photovoltaic panel accounts for the

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majority, in photovoltaic fires. Therefore, in the experiment, the focus is on the thermal radiation on the combustion characteristics of the photovoltaic panel backplane. Figure 2 fully shows the entire combustion process and residues of the sample. When the photovoltaic panel backplane is placed under thermal radiation, the heating process is similar to one-dimensional heat conduction. As the temperature rises, the back sheet film will shrink locally and generate a large amount of pyrolysis gas, shown in figure 2A. When the pyrolysis gas concentration reaches a critical value, flashover occurs, figure 2B, and then it enters the full combustion stage, figure 2C. The combustible material in the sample is a polymer, so once ignited, it burns quickly and has a high heat release rate. When the fuel is exhausted, the combustion quickly decays, figure 2D. Figure 2E shows the combustion residue. It can be seen that, except for non-combustible glass and silicon wafers, the polymers are almost completely burnt.



Figure 2. Burning processes of sample. (A) The initial phase; (B) Flashover; (C) Full combustion stage; (D) Combustion decay stage; (E) Combustion residue

3.2 Combustion characteristics

Figure 3 shows the relationship between the ignition time of the photovoltaic panel sample and the intensity of external heat radiation. In the experiment, we considered these two situations. The glass surface of the photovoltaic panel is facing the heat radiation and the back plate of the photovoltaic panel is facing the heat radiation. It can be found that the ignition time is inversely proportional to the intensity of external heat radiation. About 20KW can be regarded as a demarcation point. When the heat radiation power is lower than 20KW, the ignition time is significantly extended [3]. Another problem is that the ignition time is different for the front and back of the photovoltaic panel under different heat radiation conditions. It can be seen from Figure 4 that the backplane of the photovoltaic panel is more dangerous under heat radiation conditions. Especially, under the condition that the glass surface of the photovoltaic panel is facing the heat radiation, it can hardly be ignited below 20KW[4].



Figure 3. Evolution of ignition time versus external heat flux



Figure 4. Results under different thermal radiation (a) Mass-Loss

Figure 4 shows the mass loss and mass loss rate of photovoltaic panels under different thermal radiation, Mass loss reflects the combustion and decomposition of materials during combustion. In addition, the mass loss rate is an important indicator of the combustion test of building materials, which can reflect the pyrolysis rate of materials. Higher mass loss rate means faster pyrolysis rate and fire risk. Figure 4 shows that under higher external heat radiation, the mass loss is more sufficient, which indicates that the photovoltaic panel burns more completely. The mass loss is about 36g, 46g, 51g, 53g, respectively, under the heat radiation of 15 kW/m², 20 kW/m², 30 kW/m², 40 kW/m².



Figure 5. Heat release rate and total heat release of the sample

The heat release rate is an important parameter to evaluate the combustion of materials [5]. At present, the oxygen consumption calorimetry method [6] is the mainstream method. Figure 5 shows the transient heat release rate and total combustion heat under different external heat radiation. It can be clearly found that the external heat radiation and the peak heat release rate present an obvious positive correlation.

3.3 Analysis of toxic gases in combustion

According to the previous analysis of photovoltaic panel materials, the combustible polymers in photovoltaic panels are photovoltaic film (EVA) and back sheet film (PET OR TPT, TPE). The molecular formulas are: PET (-[OCH2-CH2OCOC6H4CO]), EVA ((C2H4) x. (C4H6O2) y) [7]. The chemical elements are concentrated in C, H, O. In addition, the TPT backsheet film contains a small amount of fluorine.

3.3.1 CO and CO₂

The transient concentration curves of carbon monoxide and carbon dioxide are shown in Figure 6. The production of carbon monoxide and carbon dioxide is closely related to external heat radiation. As shown in Figure 6a, 20 kW is an obvious demarcation point. When the heat radiation is lower than 20KW, the ignition time of the photovoltaic backplane is significantly prolonged. Before 400 seconds, no obvious carbon dioxide gas was found. With the increase of external heat radiation, the peak concentration of carbon dioxide can reach 0.47 vol% (40KW).

Corresponding to carbon dioxide, the concentration of carbon monoxide has a similar pattern. It can be found that when the external heat radiation is low (15kw), before 400 seconds, the concentration of carbon monoxide gradually increases. According to the previous ignition time, most of the carbon monoxide gas comes from the pyrolysis process before the ignition of the polymer.



Figure 6. CO and CO₂ concentration under different thermal radiation

3.3.2 SO2

According to the molecular formula of the photovoltaic panel material, no sulfur is found. According to the product data of the factory, sulfur is mainly found in additives and cross-linking agent, especially EVA film. In Figure 7, there is little difference in the peak concentration of sulfur dioxide under different external heat radiation. The maximum instantaneous peak concentration is about 6 PPM. It can be found that the instantaneous concentration curve of sulfur dioxide slightly lags behind the heat release rate curve. As the heat release rate increases, a sufficiently high temperature causes the sulfur in the crosslinker and additives to decompose and oxidize to form sulfur dioxide.



Figure 7. Concentration of SO₂ under different thermal radiation

3.3.3 HCN

Hydrogen cyanide is one of the fast and highly toxic substances in the harmful combustion products of fire. The instantaneous concentration of hydrogen cyanide is relatively low, the highest concentration is about 2PPM, as shown in Figure 8. According to known data, when the concentration of hydrogen cyanide reaches 5-20mg/m, some contacts will experience headache, nausea, dizziness and other symptoms within 2 to 4 hours .



Figure 8. Concentration of HCN under different thermal radiation

3.4 Gas toxicity evaluation

The estimation of the lethal toxic potency of fire effluents is described in detail in ISO 13344:2015. The toxic potency of smoke may be approximated by the contributions of a small number of gases has been termed the "N-Gas Model" by the US National Institute of Standards and Technology (NIST) [8].

$$L_{FED} = \frac{m[CO]}{[CO_2] - b} + \frac{21 - [O_2]}{21 - LC_{50,O_2}} + \frac{[HCN]}{LC_{50,HCN}} + \frac{[SO_2]}{LC_{50,SO_2}}$$
(1)

Where, m is the slope of the CO-vs-CO₂ curve, which depicts the increasing toxicity of CO as CO₂ concentration increases, b is the intercept of the CO-vs-CO₂ curve, which depicts the increasing toxicity of CO as CO₂ concentration increases, $[O_2]$, [HCN], $[SO_2]$ are the concentrations of various fire effluent gases. Generally, 0.3 is recommended as the critical threshold of FED value. Figure 9 shows the instantaneous value of the FED value under different heat radiation. The maximum value is about 0.09, which is far less than the safety threshold of 0.3. However, it is worth noting that the burning area of the experimental sample is relatively small. If the cumulative value is considered, the FED value will be Continued to increase.



Figure 9. FED value under different thermal radiation based on time as a function

4 Conclusion

In this paper, an experimental study was conducted on the combustion characteristics and toxic gas hazards of widely used glass panel photovoltaic modules under fire conditions, and the fire calorimetry method was used. Several important fire-based parameters were measured, such as heat release rate, ignition time, mass loss rate, and total heat of combustion. Based on the chemical composition of photovoltaic panels, especially the gas composition and concentration that may cause poisoning in photovoltaic fires, the FED value was used for quantitative evaluation. Through experiments, it was found that the main harmful gases are concentrated in CO, with a small amount of SO₂ and HCN. Surprisingly, for the expected fluorine-containing material in the backsheet film of the photovoltaic panel, no significant HF gas was detected in the experiment. In short, the strength of external thermal radiation has a great impact on the combustion properties of materials and the release of toxic gases. Higher thermal radiation means higher risks. The experimental data can be used for simulation comparison and fire assessment.

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