Future Sustainability
Open Access Journal
ISSN 2995-0473

February 2024| Volume 02 | Issue 01 | Pages 25-34
Journal homepage: https://fupubco.com/fusus
https://doi.org/10.55670/fpll.fusus.2.1.3

Future Publishing LLC

Article

Experimental study on combustion characteristics of billboard materials

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ARTICLE INFO

Article history:
Received 04 October 2023
Received in revised form
05 November 2023
Accepted 11 November 2023

Keywords:
Billboards, Combustion characteristics, Fire, PET, PVC

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DOI: 10.55670/fpll.fusus.2.1.3

ABSTRACT

Billboards are permanent facilities in large commercial buildings, indoor and outdoor public places, and in fire accidents, billboards will become the main cause of the expansion and spread of fires. To reduce the fire accidents caused by the burning of billboards, this paper conducted experimental tests on 12 commonly used billboard material types of Polyethylene glycol terephthalate (PET) and Polyvinyl chloride (PVC). Among the 12 materials, only PVC4 belongs to the range of flame-retardant materials. PVC6 has the lowest calorific value, less heat release, and a stronger fire effect than other materials. The flammability experiment shows that the ignition time of the material is positively correlated with the combustion height under the same ignition method, and the ignition time is also positively correlated with the combustion width. Under the same ignition time conditions, the flame aspect ratio using edge ignition is greater than or equal to the flame aspect ratio using surface ignition, and the fire hazard is greater. It is necessary to avoid the presence of combustibles around 250 mm to cause fire spread. The monomer combustion experiment shows that the flame spread area of PVC material is much larger than that of PET material. Among all materials, the most dangerous is PVC6, which releases the largest CO concentration and the fastest rate after combustion, produces the most flue gas within 100 after combustion and has poor flame-retardant performance. The combustion of all advertising materials releases less CO and CO_2 concentration, which can cause physiological adverse reactions in the human body but will not cause death.

1. Introduction

Billboard is a permanent facility for large commercial buildings and indoor and outdoor public places to meet the functions of guidance, publicity, and commercial activities. Due to the large number, large size, and wide distribution of billboards built indoors, outdoors, and on buildings, this kind of billboard easily becomes a source of ignition and a fuse that promotes the spread of fire after a building fire [1]. The occurrence of building fires not only brings huge economic losses but also volatilizes a large amount of toxic and harmful gases such as smoke, CO_2, CO, and hydrocarbons during the combustion process [2-4]. According to the analysis of the causes of casualties in fire accidents in the past, it is found that the number of people killed by smoke is much higher than that of people killed by high temperatures [5, 6]. Therefore, it is of great significance to study the combustion characteristics of billboards to avoid building fires and reduce property losses and casualties. Flat billboards and advertising light boxes are two common types of billboards used today [7]. Flat billboards are mainly composed of metal frames, advertising cloth, or photo paper, and metal frames are non-combustible materials. The advertising light box is mainly composed of three parts: a metal frame, auxiliary optical equipment, and a pattern printing carrier. The light box is composed of auxiliary light equipment and a pattern printing carrier. That is the electronic components in the light box, the light box piece, or the light box cloth, in which the electronic components mainly include the light source, the connecting line, the power supply, and the control board. According to the analysis of the internal composition of billboards, scholars have studied the fire caused by light sources, connecting lines, and power supply combustion [8-11]. However, in comparison, the material of advertising materials is thinner [12], and the contact area with the outside air is large, once the fire source appears, the advertising material must be ignited first. Then, it spreads to the interior or surrounding combustibles of the billboard, and the degree of fire and the consequences are more serious. However, there is a lack of research on the combustion characteristics of advertising materials, and the relevant research only involves the study of the type of advertising cloth materials. At present, the commonly used advertising materials include the base cloth formed by rolling the high-strength polyester industrial filament after bonding with polyvinyl chloride and then impregnating the base cloth into the slurry containing polyvinyl chloride resin. A base cloth made of polyester fiber and spandex cloth, and then treated with water-based and environmentally friendly polymer polyacrylic resin stitch-impregnated coating, as well as an electronic luminous light box and edge-lit ultra-thin light box. Based on the current research on billboard materials, this paper carried out experimental tests on 12 commonly used billboard material types, Polyethylene glycol terephthalate (PET) and Polyvinyl chloride (PVC)， in order to gain insight into the relevant parameters of billboard material combustion. The combustion parameters of billboard materials are obtained and analyzed through a combustion calorific value experiment, oxygen index experiment, smoke density experiment, flammability experiment, and monomer combustion experiment, which provides direction for reducing the use of flammable billboard materials and aggravating the occurrence of fire.

2. Experiment

2.1 Experimental materials

In this paper, 12 commonly used advertising materials are used for relevant experimental research, and the material numbers are named after the main raw materials of advertising materials, the relevant information is shown in Table 1.

2.2 Experimental equipment

Figure 1 shows the material combustion experimental equipment. The combustion calorific value test of the material was carried out by a 5E-C5808 oxygen bomb calorimeter. The flame retardant properties of the materials were measured by an HC-2C oxygen index meter under normal temperature and pressure conditions. The smoke density test was carried out using SCY-1 building material smoke density tester. The working pressure of the fire system was 276kPa, the fuel used was propane gas, and the timing device adopted a timer with 15s intervals. The FCK-1 building material flammability test furnace was used in the flammability test. The ignition time was 15 s and 30 s, and surface ignition and edge ignition were used. The sample size was 250 mm × 90 mm. In the Monomer combustion experiment, the auxiliary burner, far away from the material, was used to measure the heat output and smoke production of the burner. The experimental fuel used 95 % propane gas, and the data acquisition used the Agilent34970 data acquisition instrument.

Table 1. Advertising materials

Material code	Material name	Material type
PET1	Back gush light-box piece	Advertising light box
PET2	Thickened back gush light-box piece	Advertising light box
PET3	Flame retardant, lightbox sheet	Advertising light box
PET4	Waterproof positive spray lightbox piece	Advertising light box
PET5	Positive spray lightbox piece	Advertising light box
PET6	Lightbox piece	Advertising light box
PVC1	Flame retardant coarse grained cloth	Advertising cloth
PVC2	Knife scrape outer light cloth	Advertising cloth
PVC3	Knife scrape outer light cloth	Advertising cloth
PVC4	Flame retardant exterior cloth	Advertising cloth
PVC5	Flame retardant inner light cloth	Advertising cloth
PVC6	Flame retardant inkjet cloth	Advertising cloth

3. Results and discussions

3.1 Analysis of combustion calorific value

The calorific value is the heat released when the unit mass combustible is completely burned at 25 °C and 110 kPa, which is the dominant factor affecting fire behavior [13]. The larger the calorific value, the more radiant heat is generated, the faster the heating rate of the combustion environment, and the combustion intensity of the fire behavior continues to increase, which can accelerate the expansion of the fire range and the spread of the fire. Calorific value is an important indicator to evaluate the combustion characteristics of combustibles. The difference in calorific value of different materials is shown in Figure 2. The calorific value of PVC2 and PVC4 is low, and the heat released during the combustion of the material is less, which is conducive to controlling the spread of fire and can play a certain degree of fire prevention role. PVC3 has the highest calorific value, and high heat will be generated during the combustion process, which will rapidly increase the temperature of the fire environment and aggravate the fire intensity. Among the combustion calorific values of 12 materials, PVC6 has the lowest calorific value, less heat released, and a stronger fire prevention effect than other materials. The combustion calorific value of PET2, PVC5, and PET2 is high, the heat released during the combustion process is greater, and the fire resistance is poor. In general, the difference in calorific value of different materials is small, except for PVC3; billboards made of PVC are stronger than billboards made of PET materials.

3.2 Analysis of flame-retardant properties

The limiting oxygen index (LOI) is the percentage of the minimum concentration of oxygen required for combustion as a percentage of the oxygen and nitrogen mixture when the sample is flamed to combustion.

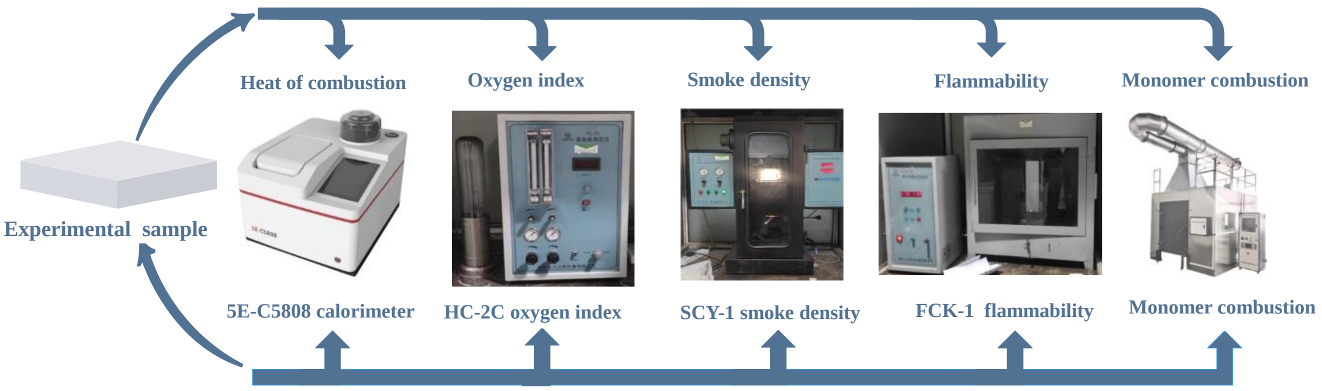

Figure 1. Experimental equipment diagram

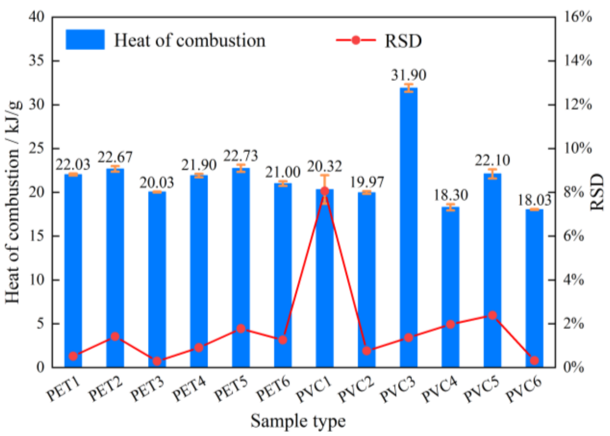

Figure 2. The calorific value of advertising materials

The higher the oxygen index is, the more difficult the material is to burn and the better the flame-retardant performance is. The lower the oxygen index, the easier the material to burn and the worse the flame-retardant performance [14, 15]. According to the composition of billboard materials and the classification of combustion grade materials, billboard grades are divided into B1 grade flame retardant materials, B2 grade combustible materials, and B3 grade flammable materials. To analyze the combustion performance level of advertising materials, avoid the use of flammable advertising materials, as shown in Figure 3 for the measured limiting oxygen index of advertising materials. The limit oxygen index range of advertising materials measured in this paper is 18.8 % -31.4 %. Among the above materials, only the oxygen index of PVC4 belongs to the range of flame-retardant materials, and PET1, PET2, PET3, PET6, PVC1, PVC5, and PVC6 are combustible materials. PET4, PET5, PVC2, and PVC3 belong to the range of flammable materials. In order to analyze the combustion characteristics of various billboard materials in more detail, it is necessary to combine monomer combustion experiments and flammability experiments to determine.

3.3 Smoke emission density analysis

The combustion of polymer materials produces a certain degree of smoke. According to the long-term accumulation of various types of fire data, the smoke and toxicity produced by combustion are the main causes of human death, and the harm is often more serious than the flame and heat generated during combustion [16-18]. The smoke density test is the main method to evaluate the smoke production performance of materials, the larger the maximum light absorption rate, the greater the amount of smoke produced during combustion [19]. The smaller the smoke density of the material, the more beneficial it is to evacuate personnel in time and ensure the safety of personnel. Therefore, it is particularly important to study the smoke density of advertising materials. Figure 4(a) shows the light absorption rate of different materials. The smoke density of PET material reached more than 80 % at 240 s.

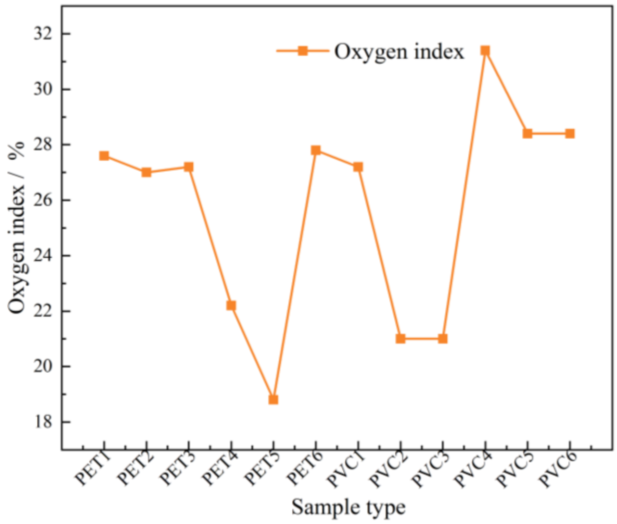

Figure 3. Oxygen index of advertising materials

The increase in the light absorption rate of PET4, PET5, and PET6 was faster, indicating that the smoke generation rate at this stage was larger, and the smoke production had exceeded 80 % in a short time. In contrast, the increased light absorption rate of PET1 and PET3 was slower. The increase rate slowed down significantly in the period of 50-100 and continued to increase to the maximum after 100, and the smoke rate was significantly lower than the first two, showing better flame-retardant performance.

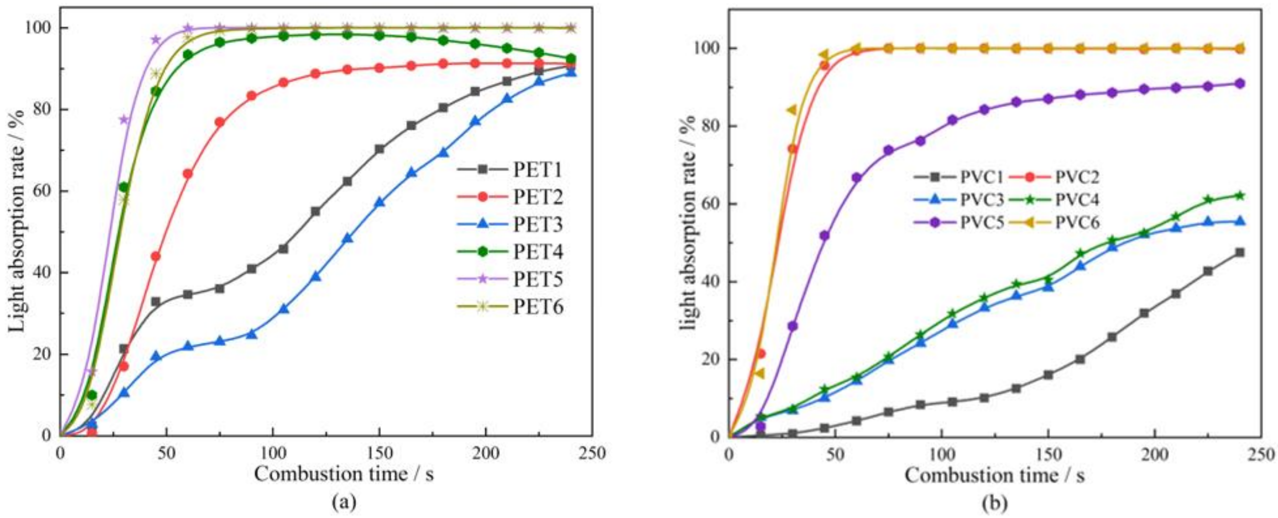

Figure 4. Light absorption rate

This is beneficial to the mitigation of the spread of fire and the improvement of fire safety to save lives and property. As shown in Figure 4(b), the light absorption curves of PVC6 and PVC2 in PVC advertising materials increased the fastest before the 50s, and the smoke production rate at this stage was large. The maximum light absorption rate of PVC1, PVC3, and PVC4 at the same time is between 47%-63%. The light absorption curve was relatively flat, the absorption amount was less, the smoke velocity was small, and it showed good flame-retardant performance. The results of the smoke density grade（SDR） of the 12 materials are shown in Figure 5.

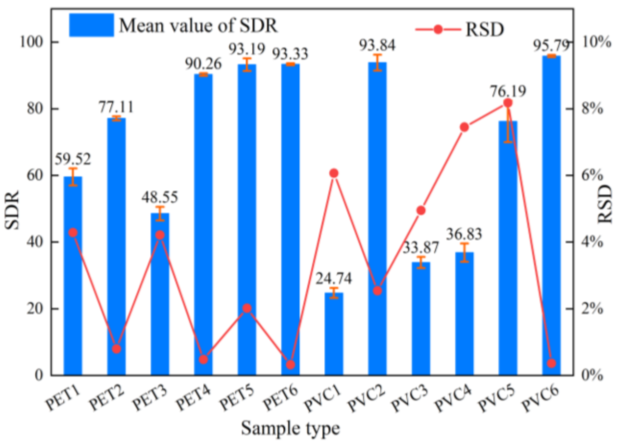

Figure 5. Smoke density grade

The SDR of PVC1 material was the smallest, indicating that the release of flue gas during the combustion of this material had a significant mitigation effect. The improved safety of this material is the highest among all advertising materials. The smoke density grade of advertising materials is less related to the basic materials in advertising materials, which is related to the processing technology and flame-retardant substances. In general, the flame retardancy of PVC advertising materials is better than that of PET materials.

Materials with high oxygen index have certain flame-retardant properties, and the smoke production rate with faster smoke generation rate is relatively large, while the smoke production rate and smoke production rate of materials with low oxygen index are relatively low. Compared with the oxygen index, it was found that the light absorption rate of PVC6 with an oxygen index of 28.4 % reached 100 % at the thickness of 6.2 mm when the experiment was carried out to 40 s. The maximum light absorption rate of PVC3 with an oxygen index of 21 % was only 55.43 % during the whole experiment. As shown in Figure 6, when the experiment was carried out for 240 seconds, the smoke production status of various materials in the experimental smoke box was significantly different. PET6, with a large oxygen index, had a larger combustion smoke production and lower visibility in the smoke box.

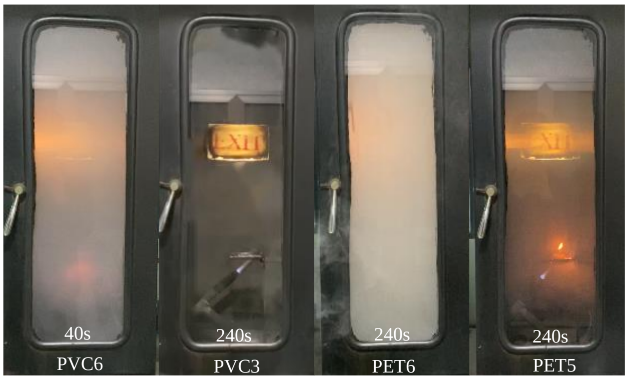

Figure 6. Experimental process diagram

3.4 Flammability performance analysis

After a fire occurs in the material, it is easy to cause the spread of fire; in order to analyze the flame spread after the burning of advertising materials and reduce the degree of fire. As shown in Figure 7, the combustion height and combustion width of advertising materials were determined by different ignition methods and ignition times. As shown in Figure 7(a), under the condition of edge ignition for 15s, the combustion height of PET5 and PVC6 reached 250mm, and the combustion to the top of the specimen had the highest risk of upward fire spread. The combustion height of PVC1 was only 58.75mm, the combustion height of PVC2 and PET3 was below 60mm, and the risk of upward spread of flame was low. Under the condition of surface ignition 15 s, the combustion height of PVC6 was up to 250 mm, and the lowest combustion height of PET3 was 68.5 mm. Under the condition of edge ignition for the 30s, PET5, PVC5, and PVC6 were burned to the top of the specimen, the combustion height reached 250mm, and the risk of upward fire spread was high. Under surface ignition conditions of 30s, PVC6 had the highest combustion height of 250mm. Compared with other advertising materials, the risk of upward flame spread was higher, PVC2 had the lowest combustion height of 75 mm, and the risk of upward flame spread was lower. In general, under the same ignition mode, the combustion height with an ignition time of 30 s was greater than or equal to the combustion height with an ignition time of 15 s. As shown in Figure 7(b), under the condition of edge ignition for 15s, the combustion width of PET5, PVC5, and PVC6 was higher than that of other materials, and the combustion width was 90mm. PET5, PVC5, and PVC6 had a higher lateral flame spread hazard than the other nine materials, while PVC1 had the smallest burning width of 16.75 mm and the lowest lateral flame spread. Under the condition of surface ignition for 15s, PET5, PVC5, and PVC6 had the largest combustion width of 90mm, and PET2 had the smallest combustion width of 24.25mm. Under the condition of edge ignition for 30s, the combustion width of PET5, PVC5 and PVC6 was higher than that of other advertising materials; the combustion width was 90mm, and the smallest combustion width was 17mm for PVC1. Compared with the previous three conditions, the burning width of PVC1 under the edge ignition method was always the minimum value of 12 advertising materials. Under the condition of surface ignition for 30s, the combustion width of PET5, PVC5, and PVC6 were higher than that of other advertising materials, with a combustion width of 90mm, and the combustion width of PET4 was the smallest, which was 25mm.

The combustion width of PET5, PVC5, and PVC6 materials was always greater than the combustion width of other advertising materials in different ignition methods and different ignition times.

Under the same ignition method, the ignition time of 30s was greater than or equal to the ignition width of 15s. In summary, the combustion height and width of the ignition time of 30s are greater than or equal to the combustion height and width of the ignition time of 15s. Under the same ignition method, the ignition time is positively correlated with the combustion height, and the ignition time is positively correlated with the combustion width. To further analyze the effect of different ignition methods on the combustion height and width of different advertising materials, the ratio of combustion height to combustion width of different advertising materials was analyzed about the ignition method and ignition time, as shown in Figure 8(a). Under the condition of the edge ignition method and ignition time of 15s, the aspect ratio of PET2 was the largest, which was 5.2, and the aspect ratio of PET5 was the smallest, which was 2.8. Under the condition of the surface ignition method and ignition time of 15s, the aspect ratio of PVC3 was the largest, 3.8, and the aspect ratio of PET5 was the smallest, which was 2.3.

In general, the aspect ratio under different ignition methods and edge ignition mode under the ignition time condition of 15s is greater than or equal to the aspect ratio under surface ignition mode. As shown in Figure 8 (b), under the condition of edge ignition mode and ignition time of 30 s, the aspect ratio of PET6 was the largest, which was 6.1, and the aspect ratio of PET5 was the smallest, which was 2.8. Under the condition of surface ignition mode and ignition time of 30 s, the aspect ratio of PET2 was the largest, which was 5.4, and the aspect ratio of PET1 was the smallest, which is 3.3. In general, the aspect ratio under different ignition modes under the condition of 30 s ignition time and the aspect ratio under the edge ignition mode was greater than or equal to the aspect ratio under the surface ignition mode. In summary, in the above 12 material aspect ratios, the aspect ratio of edge ignition is greater than or equal to the aspect ratio of surface ignition under the same ignition time conditions.

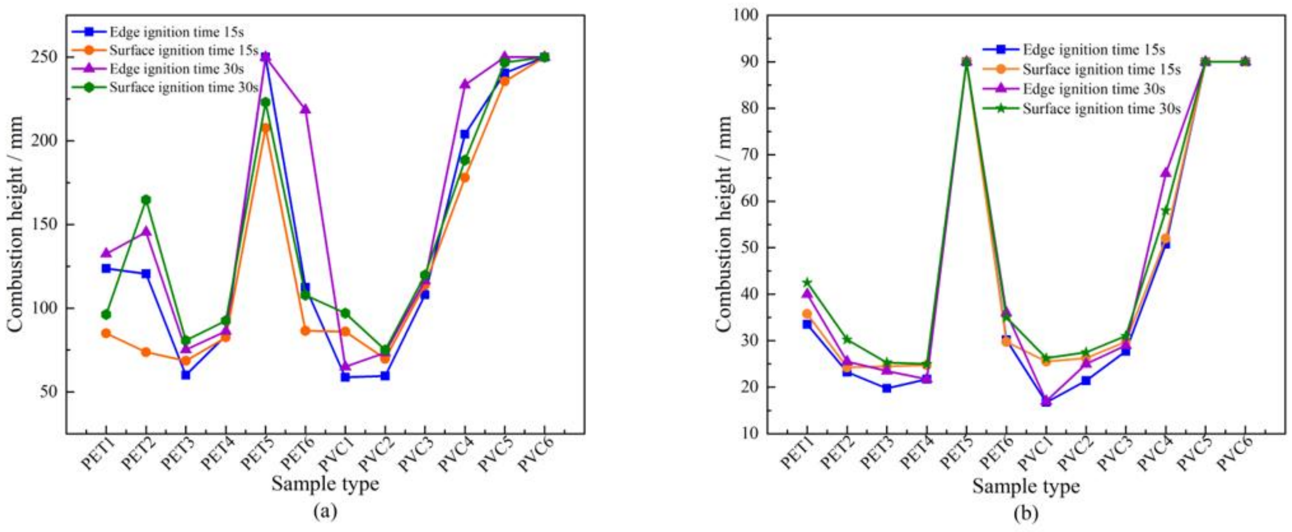

Figure 7. Combustion height and width under different ignition methods

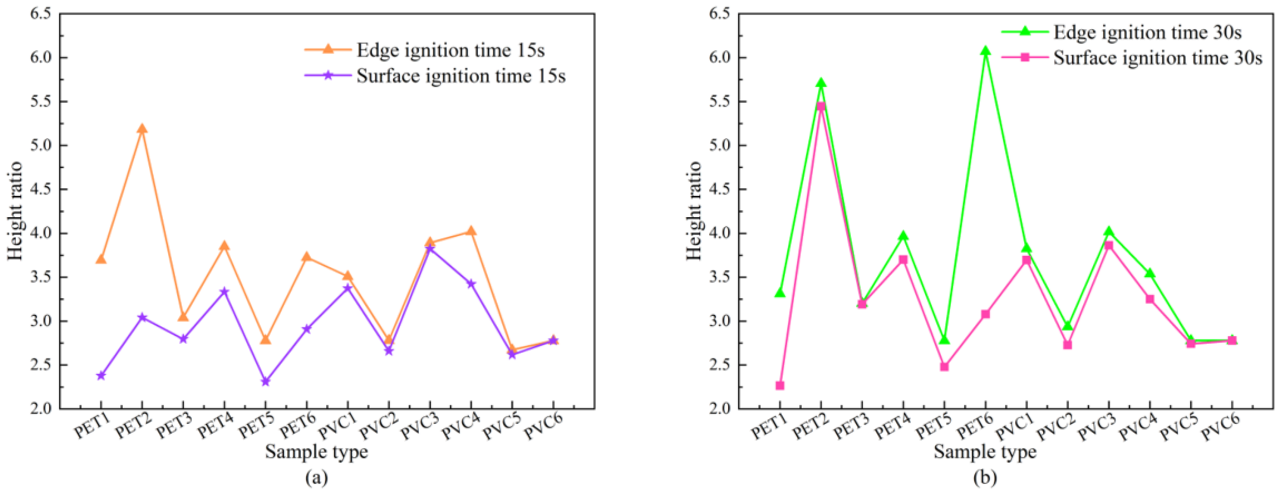

Figure 8. Combustion width-height ratio under different ignition modes

3.5 Experimental analysis of monomer combustion

3.5.1 Material combustion processes

To analyze the flame morphology of advertising ignition at different times. As shown in Figure 9 and Figure 10, when the initial ignition time of the main burner was 300 s, the flame was in a sensational state, and then the heat was transferred to the sample. After the sample absorbed the heat, the pyrolysis reaction occurred and spread along the vertical and horizontal directions. Finally, some areas stop burning due to a lack of sufficient heat. In general, the flame spread area of PVC material is much larger than that of PET material.

3.5.2 CO, CO_2 and O_2 concentration analysis

In the event of a fire, the ignited items can not only release heat but also release CO, CO_2, and other toxic and harmful gases, endangering related personal safety, so it is of great significance to analyze the substances and substance generation in the flue gas. Figure 11(a) shows the CO concentration over time when different PET materials are burned. The peak CO concentration of PET6 during combustion was up to 0.027%. All PET advertising materials will quickly drop to less than 0.005% within the last 50s after reaching the peak CO concentration. As time goes on, the CO concentration decreased slowly, and the CO concentration of some samples PET1 and PET4 increased, which was caused by the combustion of propane in the auxiliary burner. In general, the CO combustion concentration of the six PET materials is less than 0.027 %, and most of the time is less than 0.01 %. Figure 11 (b) shows the curve of CO concentration with time during the combustion of different PVC materials. PVC materials began to produce CO in 350s, and CO concentration rose rapidly before 400s, and CO concentration of 6 PVC materials stabilized below 0.006% after 450s. PVC6 reached the maximum CO concentration of PVC material at 366s to 0.046%, decreased to 0.03% after the 20s, and then dropped to 0 after 465s, and the material no longer burns. Overall, the most dangerous of all materials is PVC6, which releases the largest concentration of CO and the fastest rate of combustion, produces the most flue gas within 100s of combustion, and has poor flame-retardant properties. Figure 12 (a) shows the variation of CO_2 concentration with time during the combustion of PET material. The peak CO_2 concentration of PET5 was up to 0.425% when burned. In the 150s-300s stage, the auxiliary burner began to burn, and the CO_2 concentration in the combustion chamber increased to about 0.3 % and remained stable. At about 320 seconds, both PET and PVC materials fluctuated greatly downward because, at this time, the auxiliary burner was extinguished, and the main burner did not completely start combustion, so the CO2 concentration dropped. Figure 12(b) shows the change in CO_2 concentration over time when PVC material is burned. Among them, the peak CO_2 concentration of PVC6 during combustion was 0.67%. In general, except that the CO_2 concentration produced by PVC6 is more than 0.55 % and the maintenance time is short, the CO_2 concentration produced by PET material and PVC material is less than 0.55 %, which has limited harm to the human body. As shown in Figure 13, the O_2 concentration changed during the material combustion with time, and the oxygen consumption of the auxiliary burner was 0.3 %. PET materials burn rapidly at about 125s, PVC materials burn rapidly at about 150s, and oxygen consumption increases instantly. Comparing (a) and (b) in Figure 13, it can be found that the O_2 concentration curve profile and the CO_2 concentration curve profile are roughly mirrored on the X-axis. Most of the O_2 consumed in the combustion of the material is converted into CO_2, less CO is generated, and the advertising material burns fully during the combustion period.

3.5.3 Heat release rate analysis

Heat release rate (HRR) is the heat released during the combustion of materials per unit area, which reflects the combustion decomposition and fire spreadability of materials to a certain extent [20-22]. Figure 14 shows the heat release rate of the material over time, where the heat release rate of PET material is less than 12kW, and the heat release rate of PVC material is less than 30kW. As shown in Figure 14 (a), the rate of heat release of all PET materials during combustion decreased after reaching the first peak and then increased slowly. PET2, PET3, and PET4 exceed the first peak in the subsequent increase. This is because, during the initial combustion, the material absorbed more heat near the flame, the flame temperature was higher, and the material had the first peak.

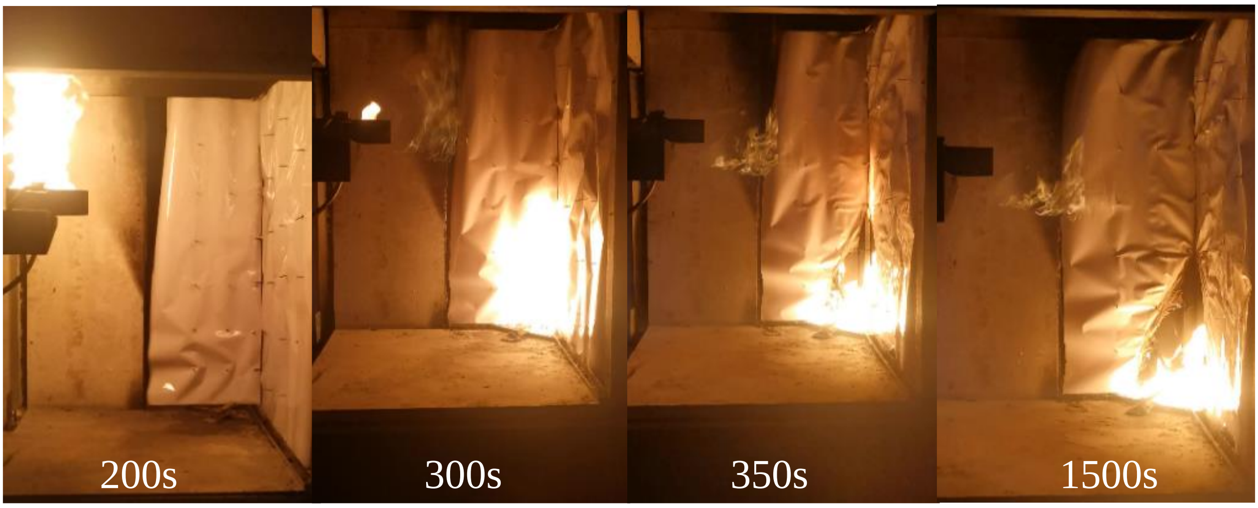

Figure 9. Combustion process diagram of PET1

Figure 10. Combustion process diagram of PVC4

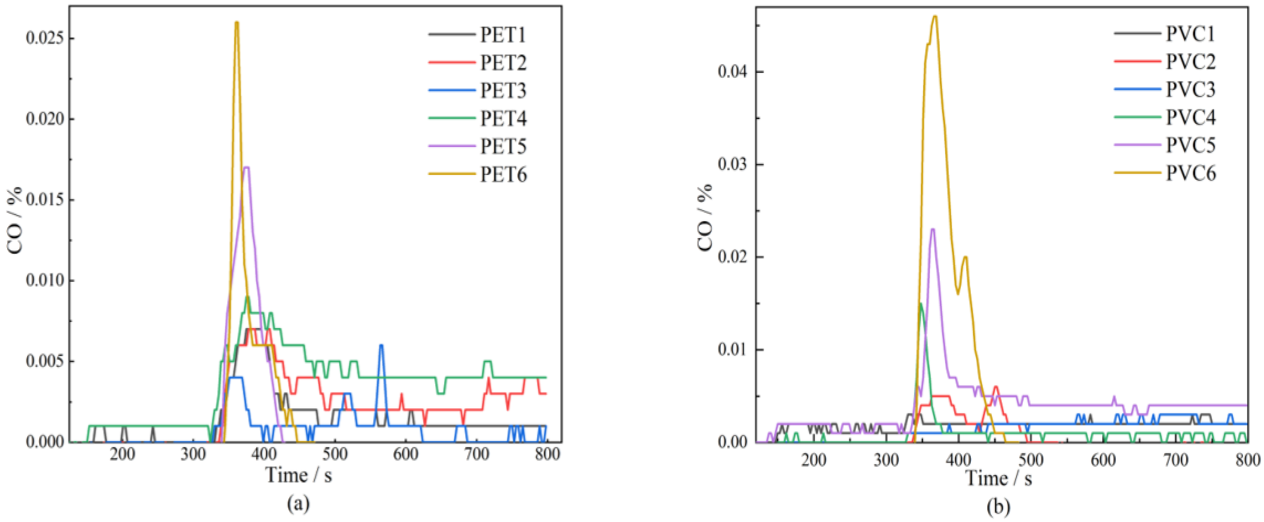

Figure 11. Variation diagram of CO concentration in single combustion test materials

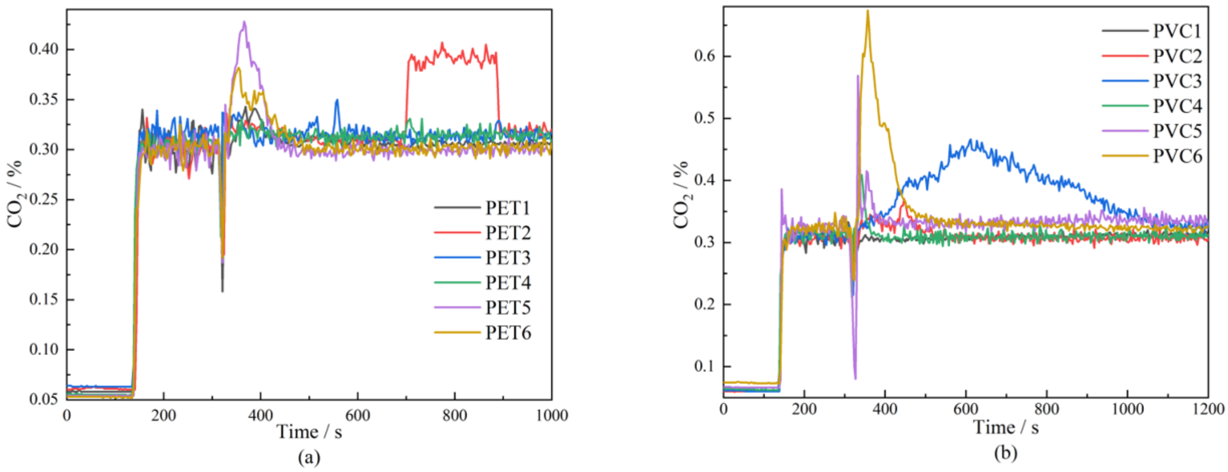

Figure 12. Variation diagram of CO_2 concentration during material combustion

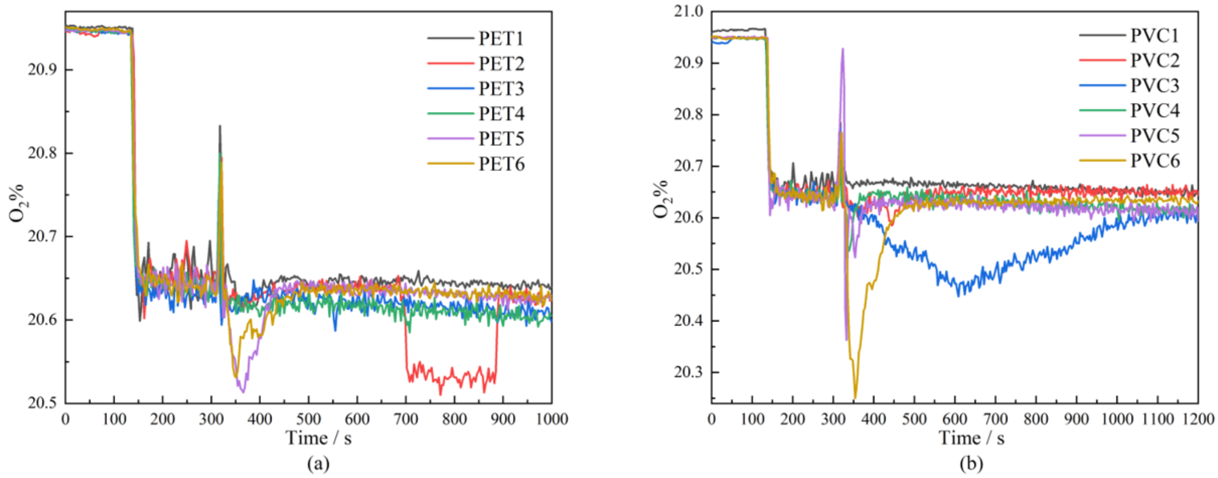

Figure 13. Variation diagram of O_2 concentration of monomer combustion test materials

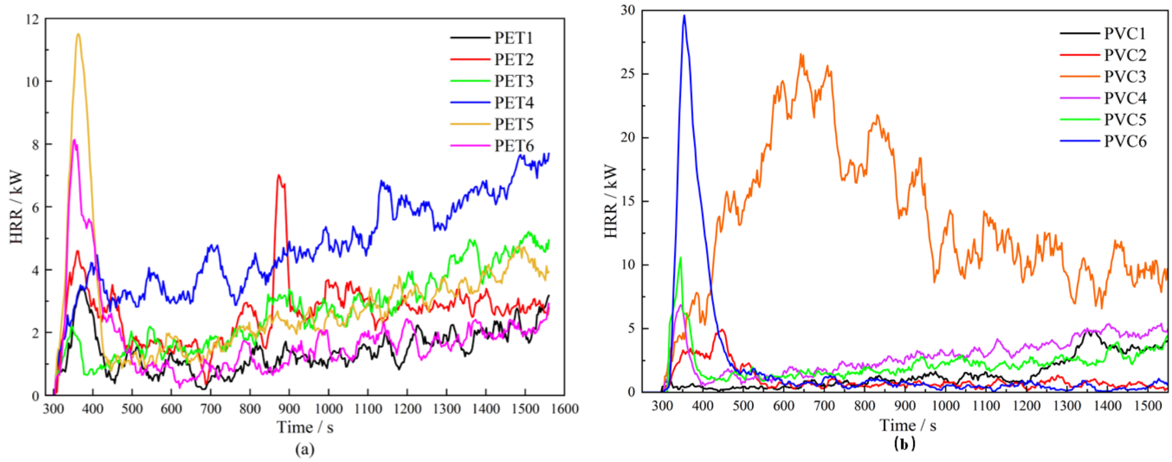

Figure 14. Material heat release rate diagram

After the oxygen between the material and the flame was consumed and reduced, the heat release rate of the material decreased rapidly. Then the air in the air supply duct filled the space again, but at this time, the combustion height released by propane combustion can no longer provide the same temperature and heat required for the material to continue combustion at the first peak, resulting in the material continuously absorbing heat and slowly pyrolytic combustion when propane was burned. Due to the long heating time of the main burner, which lasted until 1560 s, the heat release rate of some materials exceeded the first peak value in the subsequent combustion. As shown in Figure 14 (b), the overall trend of the heat release rate curve of PVC3 in PVC advertising materials is quite different from that of other sample curves. This is because the PVC3 specimen is easy to ignite, and the heat released after burning can satisfy the heat required for the flame to spread outward, so the specimen continued to spread for a long time and released more heat overall. The peak of PVC6 was close to 30kW at most, and the advertising material released a lot of heat for a short time after ignition, but the maintenance time was short because the material flame spread faster and required too much oxygen, but due to the small total mass of the material and the limited oxygen supply, it was difficult for the material to continuously released a large amount of heat for a long time.

3.5.4 Flue temperature analysis

Figure 15 is a temperature change diagram of the combustion flue of materials. As shown in Figure 15(a), after the ignition of all materials, the flue temperature first climbed rapidly to 40°C and then slowly rose to 45°C to reach a stable combustion process in the auxiliary burner. In the 300-350s, the temperature decreased rapidly. On the one hand, because the auxiliary burner is extinguished, the main burner begins to burn, and the heat released by the flame to the outside world decreases in a short time. On the other hand, because the material absorbs heat after the main burner burns, the surface temperature rises, and pyrolysis consumes heat. After 350 s, the temperature of PET2 increased by about 15 °C in the 700 s-850 s period, while the temperature of other PET materials increased slowly.

Because other PET materials are extinguished immediately from the fire, after the material close to the flame in the early stage is burned, the area far from the flame cannot be burned. As shown in Figure 15(b), the flue temperature curves of PVC3, PVC4, PVC5, and PVC6 have obvious peaks. PVC3 suddenly dropped after reaching the first high temperature of 45 °C and then slowly rose to 52 °C. The temperature peak lasted the longest, and the temperature curve at the highest temperature was sharp, indicating that PVC6 burned more intensely, and the energy release rate was faster and more focused, so the combustion temperature was also higher.

4. Conclusions

In this paper, the combustion characteristics of advertising materials are studied based on a calorific value experiment, oxygen index experiment, smoke density experiment, flammability experiment, and monomer combustion experiment. The following conclusions are obtained: (1) Among the 12 materials, only PVC4 belongs to the range of flame-retardant materials, and PVC6 has the lowest calorific value, less heat released, and a stronger fire prevention effect than other materials. PET2, PVC5, and PET2 have higher combustion calorific values, emit more heat during combustion, and have poorer fire resistance.

(2) Under the same ignition method, the ignition time of the material is positively correlated with the combustion height, and the ignition time is also positively correlated with the combustion width. Under the condition of the same ignition time, the flame aspect ratio of edge ignition is greater than or equal to the flame aspect ratio of surface ignition, and the fire hazard is greater. It is necessary to avoid the existence of combustibles around 250 mm to cause fire spread and aggravate fire.

(3) Among all materials, the most dangerous is PVC6, which releases the largest CO concentration and the fastest rate after combustion, produces the most flue gas within 100s after combustion and has poor flame-retardant performance. The concentration of CO and CO_2 released from the combustion of all advertising materials is low, which can lead to physiological adverse reactions in the human body but will not cause death.

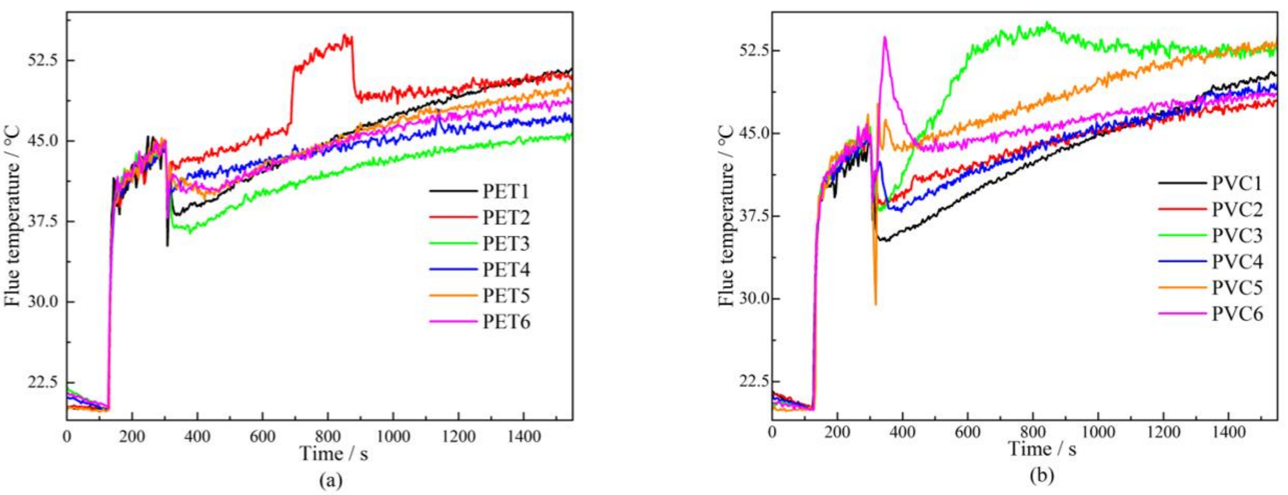

Figure 15. Temperature variation diagram of material combustion flue

Acknowledgments

The authors acknowledge the financial support provided by Central University Basic Research Fund of China (Grant No. BBJ2023015).

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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