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This is an Accepted Manuscript of an article published by Taylor & Francis in Combustion science and technology on 12 Mar 2022 (Published online), available online: http://www.tandfonline.com/10.1080/00102202.2022.2050717.

Flammability and flame spread behaviour of common fuels in Chinese historical buildings: An experimental research

Haowei Hu[a], Jingjun Shi[a], Zhenyao Qi[a], Hang Li[a], Xinyan Huang[b], Jie Ji[a,*]

[a]*State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, China*

[b]*Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong, China*

Abstract: A feature of Chinese historical buildings is the preservation of many traditional customs, such as using candles and incense burners, and decorating the rooms with some textiles. Therefore, there are both many fire sources and combustible materials indoors, which puts a huge threat to fire safety. Although some researchers have experimentally studied the ignition and fire spread characteristics of several combustible materials, to better conduct fire risk assessment in historical buildings, the dynamic burning behaviour of common fuels should be further analysed. This paper carried out experimental investigations for flammability and fire spread behaviours of combustible materials usually used in Chinese historical buildings, which are made of both natural fibre and synthetics. Considering practical applications, the size of each sample is chosen from standard-testing size to real size. It is summarized that there are large deviations among different materials due to their ingredients, textures, structures, etc. The natural-based materials are easy to catch fire and burn up quickly, and some synthetics reveal sharp increase in heat release rate. For the synthetics, as it can melt during burning, the flame spread process is accompanied by dripping. Once there are some combustibles near it, the dripping part is liable to ignite the surroundings and cause damage to cultural relics. Based on these knowledges, fire hazards of different materials in Chinese historical buildings are evaluated.

Keywords: *Chinese historical buildings, combustible material, flame spread, dripping, fire hazard*

1. Introduction

Chinese historical buildings enjoy a high reputation due to their magnificent design and unimaginable creativity, such as Potala Palace in Lhasa, and Forbidden City in Beijing. To better inherit cultural heritages, many traditional customs are still preserved, such as using candles and lanterns for illumination, and burning incense to worship ancestors. Besides, many historical buildings in China open to visitors have modern electrical appliances, including air conditioners, fans, and heating devices. The above customs have potential fire hazards. By statistics from 2009 to 2018 in China, the main causes of fires in historical buildings are electrical fires and careless use of fire, and there are some lightning strikes and other factors leading to fire accidents as well. Chinese historical buildings are

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[*] Corresponding to jijie232@ustc.edu.cn

mainly made of wooden components, and there are some combustible materials, like paintings, clothes and woven ornaments. If these materials are ignited by the above fire sources, it may cause an immeasurable loss(Fan 2001; Dong, You, and Hu 2014). Typical fire hazards in these buildings are shown in Fig. 1. Till now, China has taken many actions to protect cultural relics and historical constructions from fire accidents, such as strengthening safety inspections, prohibiting smoking, regulating the use of electrical equipment, etc., which reduce the occurrence of fire to some extents. However, fire hazards cannot be absolutely eliminated, as long as there are combustibles indoors, which will cause damage to the cultural relics and human body (Wichman 2003).


candles stove electrical appliance
wooden structure woven ornaments woven mats

Fig. 1. Typical fire hazards in Chinese historical buildings.

In order to evaluate the possible impact of the above combustibles on Chinese historical buildings and the surroundings, it is necessary to learn the combustion and fire spread characteristics of different materials. Previous literatures have carried out some researches about wooden materials (Lahtela and Kärki 2016; Regan 2021; Liu et al. 2013; Kuo and Hwang 2003), and recently, textiles and some soft materials are also paid attention because they are common and easy to be ignited as well (Yang and He 2012; An et al. 2010; Kandola et al. 2006; Wulff et al. 1973). You et al. (You, Hu, and Song 2007) compared 47 kinds of hanging decorative textiles in Tibet historical buildings for their pyrolysis and combustion characteristics, such as heat release rate (HRR), mass loss rate (MLR), peak gas volume fraction, etc. They showed that most of the fabrics have high HRRs and fast burning rates. For different types of fabrics, the burning behaviors deviate among them, and there are many factors contribute to it, such as the ingredients and processing methods (Galaska, Horrocks, and Morgan 2017; Dorez, Taguet, and Ferry 2013). Galaska et al. (Galaska, Horrocks, and Morgan 2017) measured the temperature and HRR of several fabrics made of cellulose-based and protein-based fibres, and showed that the HRR of the two types of materials was different due to their fibre processing methods and physical and chemical structures. Dorez et al. (Dorez, Taguet, and Ferry 2013) studied the ingredients of different natural fibres, and concluded that by adding lignin in natural fibres, it took less time to be ignited compared with pure natural fibre materials.

Dynamic flame spread behaviour is another important topic, which is usually conducted by vertical or horizontal burning test (Cui, Zhu, and Gao 2016; Cui 2018; Huang 2017). Some researchers carried out experiments on soft materials to study the mechanism of flame spread, and found many interesting burning behaviors such as fire accelerating or self-extinguishing phenomenon (You 2008; Ortega et al. 2021; Moussa, Toong, and Backer 1973; Ohalele et al. 2021). During the heating process, some materials burn with melting and dripping (You 2008; Ortega et al. 2021; Moussa, Toong, and Backer 1973), and their tensile strength may also change (Ohalele et al. 2021). It shows that flame spread behaviors among different materials are also affected by many factors. For example, Hirschler et al. (Hirschler, Zicherman, and Umino 2009) studied the flame propagation of a series of cellulose fibre fabrics and blended fabrics, and showed that the fire behavior was more dependent on the area density of fabrics than the chemical composites.

Although some studies have been carried out on common fabrics, in Chinese historical buildings, more specific materials should be contained, such as artworks, woven ornaments, construction products, and so on. Due to their ingredients and textures, these fuels may reveal different burning behaviors and affect the accuracy of fire risk assessment. Therefore, deeper understanding of dynamic burning characteristics for these materials should be evaluated. Based on these considerations, this work studied the ignition, combustion and flame spread process of common fuels usually used in Chinese historical buildings with fire propagation apparatus (FPA) test and vertical burning test at standard-testing size. To better conduct fire risk assessment, full-scale tests were also carried out to learn the combustion characteristics under the real size of combustible materials frequently used. Twelve representative materials, including painting and calligraphy, clothes, decorations, and construction supplies, are chosen for comparison. By analyzing the dynamic burning behaviors and summarizing potential risks of the materials, we can give a fire hazard evaluation for different materials and provide profound suggestions for fire safety.

2. Materials and Methods

2.1. Materials

In this work, 12 types of materials used in Chinese historical buildings were chosen, which were ranked by calorific value in Table 1. These materials are made of different kinds of ingredients, such as natural plant fibre (Material-1 to 3), protein (Material-4), and synthetics (Material-5 to 12). For the relatively pure and natural materials (Material-1 to 4), the calorific values are usually below 20 MJ/kg. For the polymers, their calorific values are higher, especially for Material-11 and 12. By comparing these materials, this work can discuss the effect of ingredients, hanging shapes (Material-5 and 6) and structures (Material-12), as described in Table 1.

Table 1. Materials used in this work.

	Material name	Main ingredient and description	Calorific value (MJ/kg)
1	Rice paper	Natural fibre	15.44±0.03
2	Cotton cloth	Natural fibre	15.51±0.03
3	Kraft paper	Natural fibre, coated with paints	18.94±0.12
4	Silk scarf	Protein	19.02±0.05
5	Ornament-1	Polyester, hanging decorations	21.45±0.67
6	Ornament-2	Polyester, hanging decorations, with a hollow cylindrical shape	22.14±0.39
7	Pennant	Flocking cloth with polyester	22.53±0.69
8	Clothes-1	Polyester	22.51±0.11
9	Clothes-2	Linen and chemical fibres	22.72±0.05
10	Clothes-3	Chemical fibres and cotton	22.74±0.06
11	Rainproof cloth	Plastic	39.46±0.07
12	Nylon netting	Nylon, used as construction supplies, with sparse structure	44.22±0.14

2.2. *Combustion test with FPA*

FPA was used in this work, which is mainly composed of a radiation heat source, a combustion chamber, a weighing system, and a gas analyzer. The measurement principle of FPA is according to the fire-test-response standard (ASTM 2019). Before heating, all the tested samples were placed inside a container with insulations, exposing only one surface with an area of 10 cm×10 cm. The total mass of the material was controlled at 11±0.5 g by stacking multiple layers of material. The sample was placed on a mass balance. Four radiant heaters surrounded the samples to provide a constant heat flux of 20 kW/m^2, which was a moderate and representative value usually used in combustion tests (Hedayati, Yang, and Zhou 2018; Ohalele et al. 2021). During the test, a pilot was placed around 1 cm above the sample surface, and air was pumped into the chamber to supply an aerobic environment for combustion. After ignition, the pilot was moved away, and the combustion product can be analyzed by the gas analyzer. Basic combustion parameters, such as HRR, MLR, CO_2 production rate(cO_2P), and CO production rate(cOP), can be obtained along the whole combustion process. A DV was located near the sample to record the burning process. Each test was repeated third times to ensure the repeatability.

2.3. *Standard vertical burning test*

The standard vertical burning test was carried out according to IEC60695-11-10 and GB/T5455. During this test, the 12 materials were cut to a size of 300 mm×89 mm. All the samples were vertically fixed to a clamp, as shown in Fig. 2. A Bunsen burner was used as the ignitor. The angle of the ignitor was adjusted to 45 degrees to the tested sample, and the length of the flame was controlled at 4 cm. During the test, the ignitor was manually controlled to approach the lower side of the sample, and after the ignition, it was moved away. A ruler was fixed on one side of the clamp to measure the burning length, and after the test, the average flame spread rate was calculated as the ratio of the maximum burning length to the duration time of the open flame. A DV was also located near the sample to record the burning process. Each test was repeated 3-5 times to ensure the repeatability.

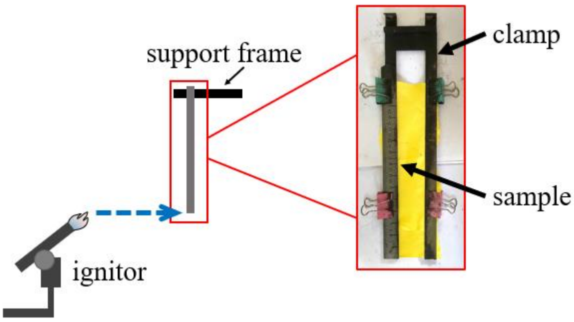

Fig. 2. The standard vertical burning test.

2.4. Full-scale test

The full-scale test was conducted to investigate the burning behavior of each material with the real size in historical buildings. The experimental system is shown in Fig. 3. All the samples were hung from the upper side, and a candle acting as a fire source was placed below it. During the burning test, the fire source was raised by controlling the mobile platform until the flame contacted with the bottom of sample. A DV was placed in front of the sample to record the dynamic flame spread process, and combustion product was collected to gas analyzer above it. On the back side of the sample, there were five K-type thermocouples located vertically along the centerline against the surface of the sample, and the lowest one was flush with the bottom of the material. Four thermocouples and radiometers are placed close to the sample, whose intervals are shown in Fig. 3. Each test was repeated third times to ensure the repeatability.

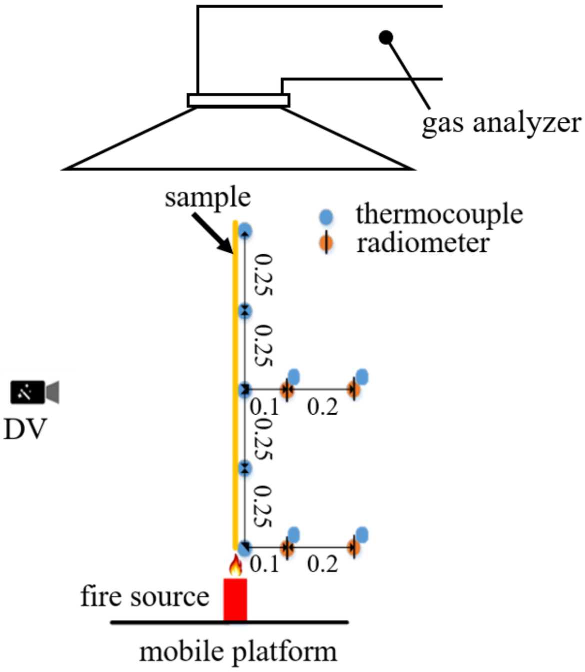

Fig. 3. The full-scale test from the side view (unit: m).

3. Results and discussion

3.1. Material flammability and burning behaviour during FPA test

Typical burning behaviors of different materials are shown in Fig. 4. For the materials mainly made of natural fibre, such as paper (Material-1 and 3) and cotton cloth (Material-2), their combustion process revealed the same trend. Take Material-1 as an example (Fig. 4(a)), during the heating, this material gradually pyrolyzed, and there was almost no deformation in the initial stage (as at 240 s). Then, the open flame appeared firstly near the pilot with a highly charred area at 310 s. The burned area extended quickly, leading to the curling and deformation of the sample (as at 360 s). After 420 s, the fire was close to extinct, and white ashes formed as residue.

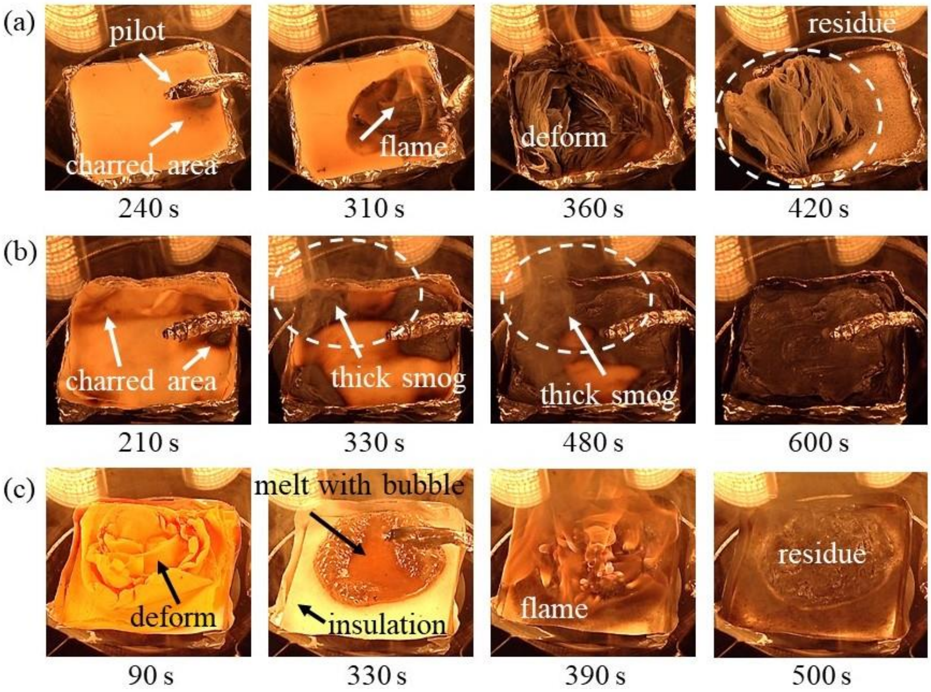

Fig. 4. Typical combustion behaviors among different materials: (a) Material-1, rice paper, (b) Material-4, silk scarf, and (c) Material-9, clothes-2.

For the textile made of protein (silk scarf, Material-4), during the whole heating process, there was no obvious deformation of the material due to its softness, as shown in Fig. 4(b). As the time went by, the sample gradually pyrolyzed and charred, as at 210 s. Then, the area undergoing pyrolysis continued to expand, and there was thick smog inside the FPA chamber. Open flame can be hardly observed in the whole process.

For Material-5 to 12, which are all synthetics, their burning behaviours are obviously different from Materials-1 to 4, as shown in Fig. 4(c). Take Material-9(clothes-2) as an example, under the heat radiation, this material deformed rapidly before the flame appeared(as at 90 s). This material can curl upward and converge towards the centre, and the pyrolysis gas was little at this period. At the 330 s, the curling sample had already melted to viscous liquid, and with the heating, bubbles started to appear due to boiling. At this time, the amount of pyrolysis gas increased. When the bubble broke, a higher-concentration gas can be released and ignited, leading to a more intense burning compared with Material-1, as shown at 390 s. As the liquid had a strong fluidity, the melting materials may increase the flame spread area with the flow of liquid, and sufficient cautions should be taken for this type of material. Finally, the flame gradually extinguished.

For the 12 materials in this work, typical combustion properties during FPA test are shown in Table 2, including the ignition time, total heat release (THR), peak HRR, mass loss, peak MLR, etc. The ignition time was obtained from the video as the appearance time of the open flame, which can reveal the difficulty of the material to combust it with a pilot under a specific heat flux. Among the tests, Material-3 (the Kraft paper) took the least time (138 s) to be ignited, while Material-4 (silk scarf) was the hardest to combust. For Material-1 to 3, which are mainly made of natural fibre, their ignition time and flame out time all deviated from each other. Rice paper and cotton cloth are soft, while Kraft paper is crisper and painted. This discrepancy may explain the differences among the materials due to their hardness, the use of paint, and their processing methods. For the polymers and other synthetics, the discrepancy for the same material (shown as the Standard Error of Mean, SEM) was large in the three repeated tests. For the rainproof cloth, the SEM for the ignition time is up to 73.2 s, which may be explained by the randomness of curling, melting and bubbling. Generally, there are large differences among the materials, and the factors to affect the trend of parameters are complex. The natural fibre-based materials are easier to be ignited compared with the synthetics, and the protein cannot be ignited during the test.

Table 2. Typical combustion properties for each material during FPA test.

Material		Ignition time (s)	THR (MJ/m^2)	Peak HRR (kW/m^2)	Mass loss (g)	Peak MLR (g/s)
1	Rice paper	282±12.7	9.00±0.45	132.9±14.46	9.27±0.16	0.18±0.005
2	Cotton cloth	170±18.2	10.70±0.38	129.7±3.93	9.94±0.04	0.21±0.005
3	Kraft paper	138±18.4	14.23±0.58	186.5±5.36	9.52±0.24	0.23±0.025
4	Silk scarf	/	/	/	4.56±0.45	/
5	Ornament-1	295±8.2	14.21±0.60	135.5±3.09	8.66±0.09	0.20±0.035
6	Ornament-2	304±9.9	14.55±0.42	136.4±5.36	9.17±0.11	0.17±0.005
7	Pennant	223±24.2	13.36±0.86	117.3±4.82	8.60±0.37	0.21±0.007
8	Clothes-1	404±15.5	10.54±0.55	155.2±9.92	7.52±0.19	0.24±0.033
9	Clothes-2	373±27.0	13.36±0.61	199.0±9.16	8.76±0.51	0.26±0.012
10	Clothes-3	559±33.1	10.52±0.38	181.8±19.45	6.63±0.64	0.31±0.018
11	Rainproof cloth	227±73.2	20.87±3.30	126.3±15.46	8.43±0.91	0.09±0.004
12	Nylon netting	276±19.1	19.72±3.49	103.8±18.33	8.39±1.17	0.16±0.032

The HRR and MLR in Table 2 were analysed combined with time, as shown in Fig. 5(a) and(b), which are grouped by the calorific value. For the HRR, before the ignition, the value fluctuated around zero. Once the material was ignited and open flame occurred, HRR raised quickly, as shown in Fig. 5(a). For the Material-1 to 3, the HRR raised rapidly with the ignition of the combustible gas, and then it dropped gradually, until the flame was out. Among them, Material-3 (Kraft paper) has the highest peak HRR with around 186.5 kW/m^2, and its THR is the highest as well. For Material-4, as it was not ignited in the test, its HRR fluctuated around zero during the whole time. For the materials with the calorific value ranges from 20 to 25 MJ/kg (Material-5 to 10), the peak HRR was higher for most of the materials compared with natural fibre-based material. For Material-8 and 10, there was an extra quick decrease period after the rise of HRR, as shown in Fig. 5(a), which implies a centralized heat release process accompanied by melting and boiling, and the peak HRR can achieve 199.0 kW/m^2 for Material-8. For the samples with the calorific value more than 25 MJ/kg (Material-11 to 12), as can be seen in Table 2 and Fig. 5(a), their HRR gradually decreased after reaching the peak, and the peak HRRs were lower than other materials. However, their THR is higher for around 20 MJ/m^2.

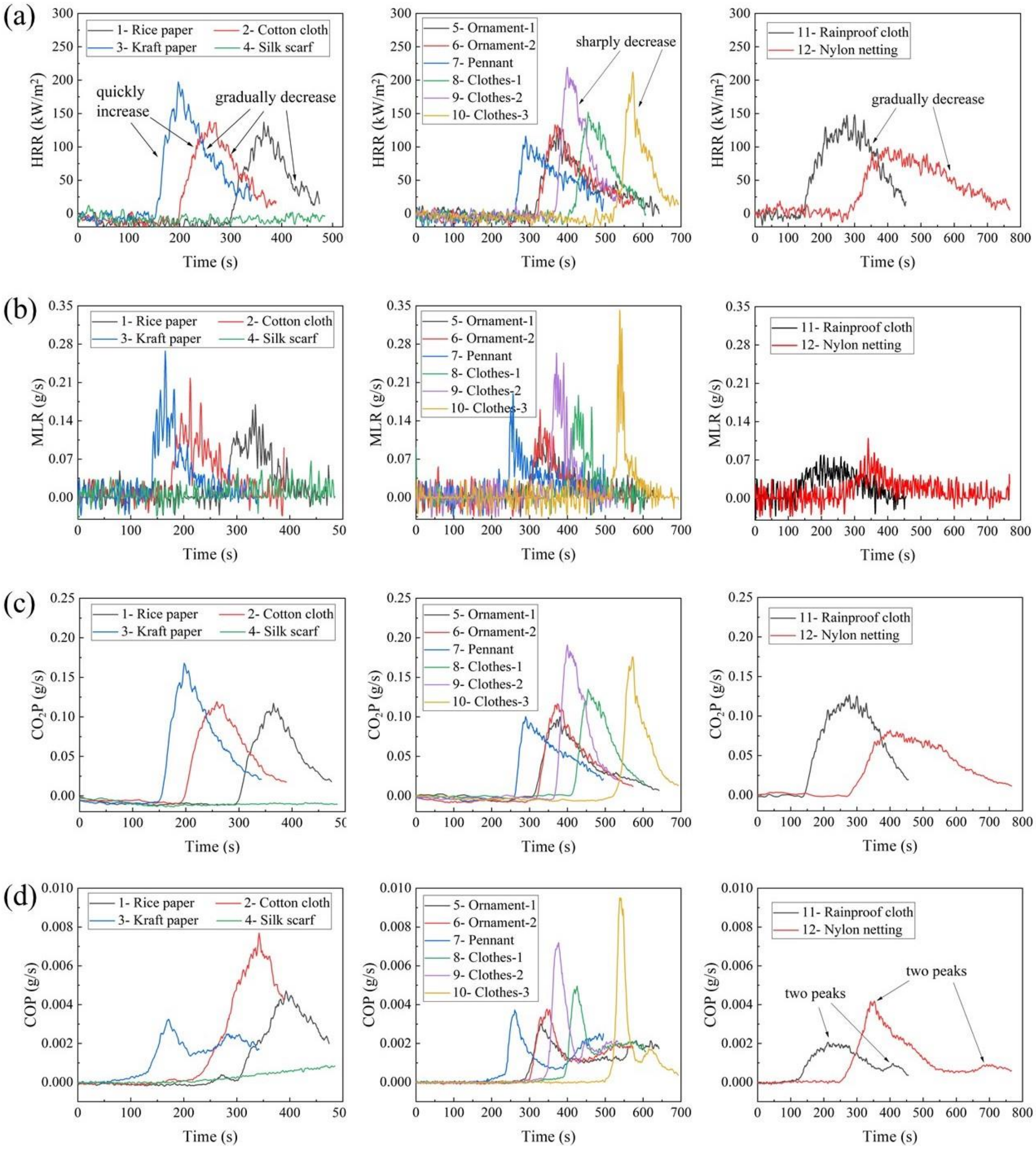

Fig. 5. Typical parameters change during the FPA test, (a) HRR, (b) MLR, (c) CO_2P, and (d) COP.

As can be seen from Fig. 5(b), for most of the materials, MLR changed from 0 to 0.4 g/s with time. The trend of MLR change with time was generally consistent with HRR, and a higher HRR corresponded to a larger MLR. For all the materials, MLR fluctuated during the test, which could be explained by the charring, deforming and melting of the samples, and the accuracy of the balance. Besides, as shown in Table 2, we also reveal the mass loss during the test. As the initial mass for each material was kept constant, with a higher mass loss, the residue is less. For natural fibre-based materials, the combustion is more sufficient with less solid residue.

To analyse the combustion product, the change of CO_2P with time of each material is shown in Fig. 5(c). Compare Fig. 5(a) and (c), the change of CO_2P has a same trend as HRR. After the materials were ignited, heat was sharply released with a large generation of CO_2. For most of the materials, CO_2P was in the range up to 0.2 g/s, except for Material-4. Different from CO_2P, COP revealed another trend, which had two peaks during the whole test, and the first peak was consistent with the peak of HRR, as shown in Fig. 5 (d). The reason for the second peak in COP may be explained by the generation and crack of chars to change the supply of the O_2. The maximum value of COP was below 0.01 g/s, which is much lower than CO_2P.

3.2. Standard vertical burning test for flame spread characteristics

For the standard vertical burning test, typical characteristics of each material are shown in Table 3, including the burning length, flame duration time, average flame spread rate, and the dripping characteristics. The 30.0 cm of the burning length means burnout of the materials, and the average flame spread rate was the burning length divided by the duration time of the open flame. From this table, there were large deviations among the materials. For the natural fibre-based materials (Material-1 to 3), they were easy to burn out with a relatively high average flame spread rate, while for the silk and some synthetics, flame cannot sustain for a long time. For the materials without burnout, the open flame will gradually extinguish as long as the ignitor was moved away. Therefore, their average flame spread rate was not calculated as they cannot self-sustain, which we will show below.

To have a better understanding, Fig. 6 shows typical flame spread behaviours of the materials. For the natural fibre, take Material-2 as an example. As shown in Fig. 6(a), during the burning process, the flame quickly developed and elongated within 5 s, leaving many embers in the burned area. After 16 s, Material-2 totally burned out, and there was no residue dropping during the whole combustion process. Compared with Material-1 to 3, Material-1 has a much higher flame spread rate than Material-2 and 3. It can be explained that rice paper has low density, therefore, it is much easier to be ignited and burn, and its flame spread rate is higher than other materials.

For the silk (Material-4), just like the trend in the FPA test, its combustion characteristics were different from others. After ignition, the place of the sample contacted with the fire can be easily ignited and the burning length can reach 16.5 cm within 12 s. However, as the flame on the ignited site was out, the flame was hard to spread, and it can only sustain for a short duration, as shown in Fig. 6(b).

Table 3. Typical characteristics of each material during the standard vertical burning test.

	Material	**Burning length(cm)**	**Flame duration time (s)**	**Average flame spread rate(cm/s)**	**Dripping**
1	Rice paper	30.0	5.1±0.04	5.94±0.06	No
2	Cotton cloth	30.0	15.0±0.70	2.01±0.13	No
3	Kraft paper	30.0	29.5±0.35	1.02±0.02	No
4	Silk scarf	16.5±1.5	11.8±0.53	/	No
5	Ornament-1	30.0	16.5±2.48	1.82±0.06	Yes
6	Ornament-2	30.0	18.1±0.71	1.63±0.11	Yes
7	Pennant	30.0	23.1±0.71	1.31±0.06	No
8	Clothes-1	30.0	16.0±0.70	1.88±0.12	Yes
9	Clothes-2	10.0±2.5	13.0±0.71	/	Yes
10	Clothes-3	7.9±2.6	3.1±0.67	/	Yes
11	Rainproof cloth	10.6±7.4	9.0±2.83	/	Yes
12	Nylon netting	4.3±2.3	2.5±0.35	/	No

For the chemical synthetics, it seems that most of the synthetics underwent melting, and the melting part may detach from the material, which is called dripping, as shown for two clothes in Fig. 6(c) and (d). However, Table 3 shows that the flame spread length may deviates among the materials. For Material-8 to 10, their calorific values are close to each other, while the flame had different burning lengths and spread rates. For Material-8, it was easy to be ignited, and the flame propagated accompanied by dripping along the whole burning process, as shown at 11 s in Fig. 6(c). For Material-10, it also dripped, as shown at 19 s in Fig. 6(d). However, it cannot totally burn out. This can be explained that before the reach of the fire, the preheated unburned area in this material had already melted and dropped, which inhibited the fire spread, as shown in Fig. 6 (d). This deviation may be caused by different ingredient ratios. Besides, for the materials with higher calorific value, such as Material-11 made of plastic, and Material-12 made of nylon, their burning behaviours are also different. For Material-11, it revealed poor repeatability with around 15 cm deviations among the repeated test. The fire spread of this material is random, which may be due to its complex ingredients. And for Material-12, as shown in Fig. 6 (e), there was an obvious spark during ignition. As the ignitor was moved away, the nylon netting melted, while there was no flame, and the burning process lasted for only 3 s. This may be because the structure of the nylon netting is very sparse, which is adverse for the flame spread.

Compare with all the materials from Table 3 and Fig. 6, materials used in historical buildings are easily ignited when exposed to a fire source. The natural fibre materials burn fast and can easily burn out, while most of the chemical ingredients will drip regardless of burnout. Due to the high temperature of the dripping, it is liable to ignite the surrounding combustibles, and lead to a wider range of fire accidents, which we will discuss in the next section.

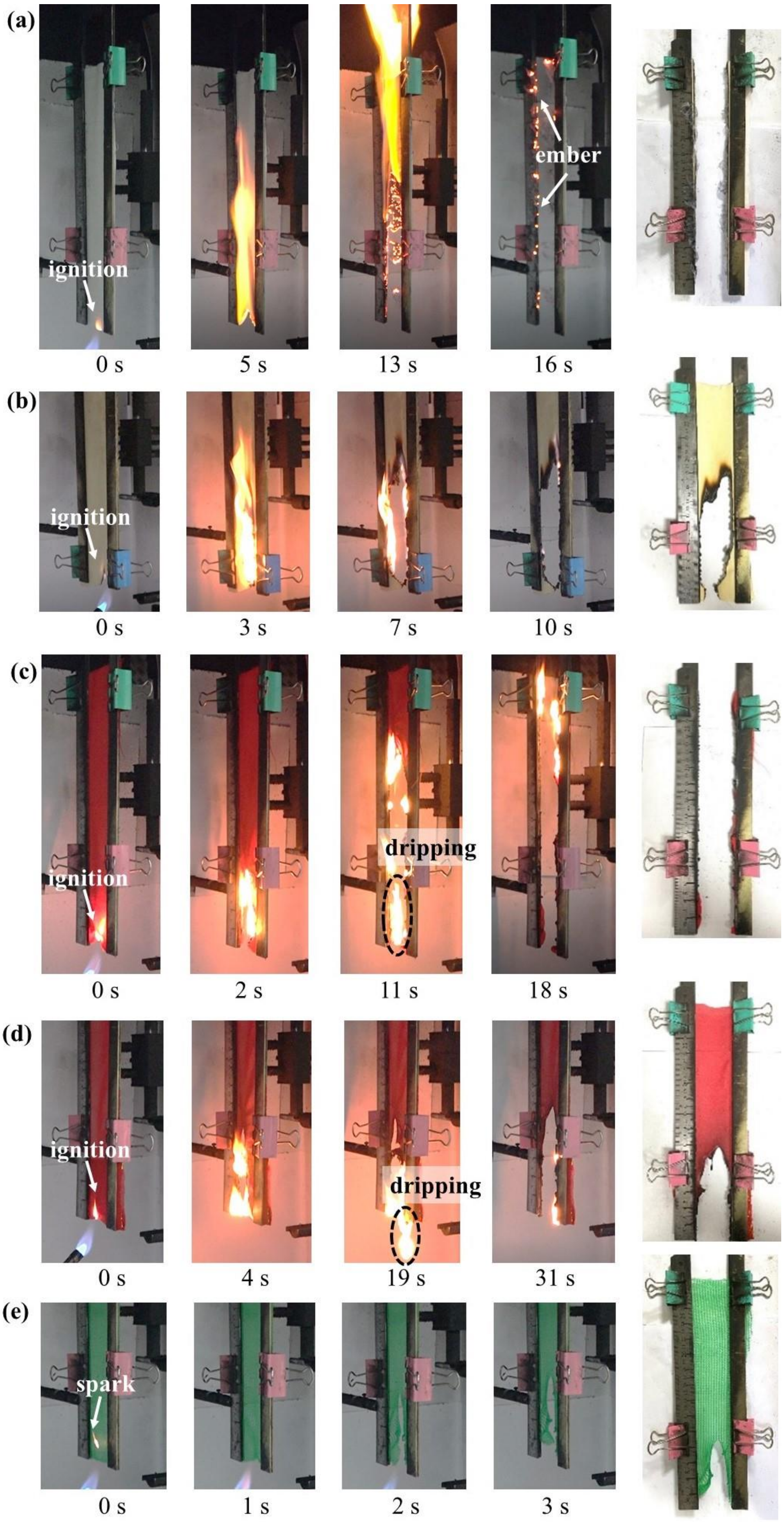

Fig. 6. Flame spread behaviors during the standard vertical burning test.(a) Material-2(cotton cloth), burnout without dripping.(b) Material-4 (silk scarf), no burnout without dripping.(c) Material-8(clothes-1), burnout with dripping. (d) Material-10(clothes-3), no burnout with dripping. (e) Material-12 (nylon netting), no burnout without dripping.

3.3. Full-scale test for flame spread characteristics

In Chinese historical buildings, there are many long-lasting fire sources as mentioned before, such as candles, censers, stoves, etc., which give a sustaining threat to the fire accident. Therefore, in this section, candles were used as a long-time fire source, and full-scale tests with real size of the materials for practical applications were carried out to obtain the realistic characteristics of the ignition and flame spread process. The size of each material is listed in Table 4, and the descriptions of the burning process for all the materials are also shown in this table. It can be summarized that for most of the material, typical burning phenomenon at full-scale are in accordance with the small-scale tests. For example, the natural fibre materials can burn quickly and completely, the silk cannot sustain flame spread, and the synthetics are easy to melt as dripping. However, the THR and peak HRR of some materials are different from the small-sized samples. Now we will analyse the characteristics of each material combined with typical burning behaviours shown in Fig. 7.

Table 4. Characteristics of each material during the full-scale test.

	Material	Height (cm) × Width (cm)	Typical burning phenomenon	THR (MJ)	Peak HRR (kW)
1	Rice paper	100×60	Flame spreads firstly in the vertical direction, complete burnout within 30 s	1.5±0.01	61.8±1.43
2	Cotton cloth	150×70	Flame spreads vertically, complete burnout within 80 s	1.7±0.05	48.0±3.68
3	Kraft paper	120×70	Flame spreads vertically, complete burnout within 200 s	6.2±0.50	114.8±13.31
4	Silk scarf	100×60	No flame spread	/	/
5	Ornament-1	87×100	Flame spreads quickly and randomly with dripping, complete burnout within 400 s	2.5±0.01	18.5±0.95
6	Ornament-2	75×Φ80	Flame spreads quickly and randomly with dripping, complete burnout within 800 s	6.2±0.24	30.6±3.51
7	Pennant	120×80	Flame spreads vertically, complete burnout within 180 s	2.1±0.17	22.0±1.10
8	Clothes-1	150×70	Flame spreads quickly and randomly with dripping, complete burnout within 400 s	3.3±0.22	14.9±0.81
9	Clothes-2	150×60	Flame spreads randomly with dripping, complete burnout within 800 s	4.6±0.29	12.3±1.50
10	Clothes-3	150×70	Flame spreads quickly and randomly with dripping, complete burnout within 600 s	3.1±0.63	9.6±1.44
11	Rainproof cloth	100×80	Flame spreads randomly with dripping, complete burnout within 600 s	2.6±0.38	10.8±0.61
12	Nylon netting	90×90	Local combustion with dripping	0.02±0.001	0.69±0.01

For the natural fibre-based materials (Material-1 to 3), there is a uniform tendency that the flame spreads quickly without dripping, and the materials can burn out completely. For Material-1, it was liable to be ignited during the test, and the flame can develop and extend its magnitude within a short time, as can be seen from Fig. 7(a), which is in accordance with the vertical burning test. After the ignition, the fire spreads upward firstly with the effect of the buoyancy force (at 4 s). Then, it enlarged to the lateral sides (at 8 s), and the flame height increased as well. Due to a large temperature difference within the sample and a high softness of its texture, this material was easy to curl (at 8 and 9 s). The intensified combustion process lasted until the flame is extinct. From Table 4, it can be seen that the peak HRR for this type of material is high as all the area of this material was nearly ignited together, and the highest peak HRR can reach 114.8 kW for Material-3.

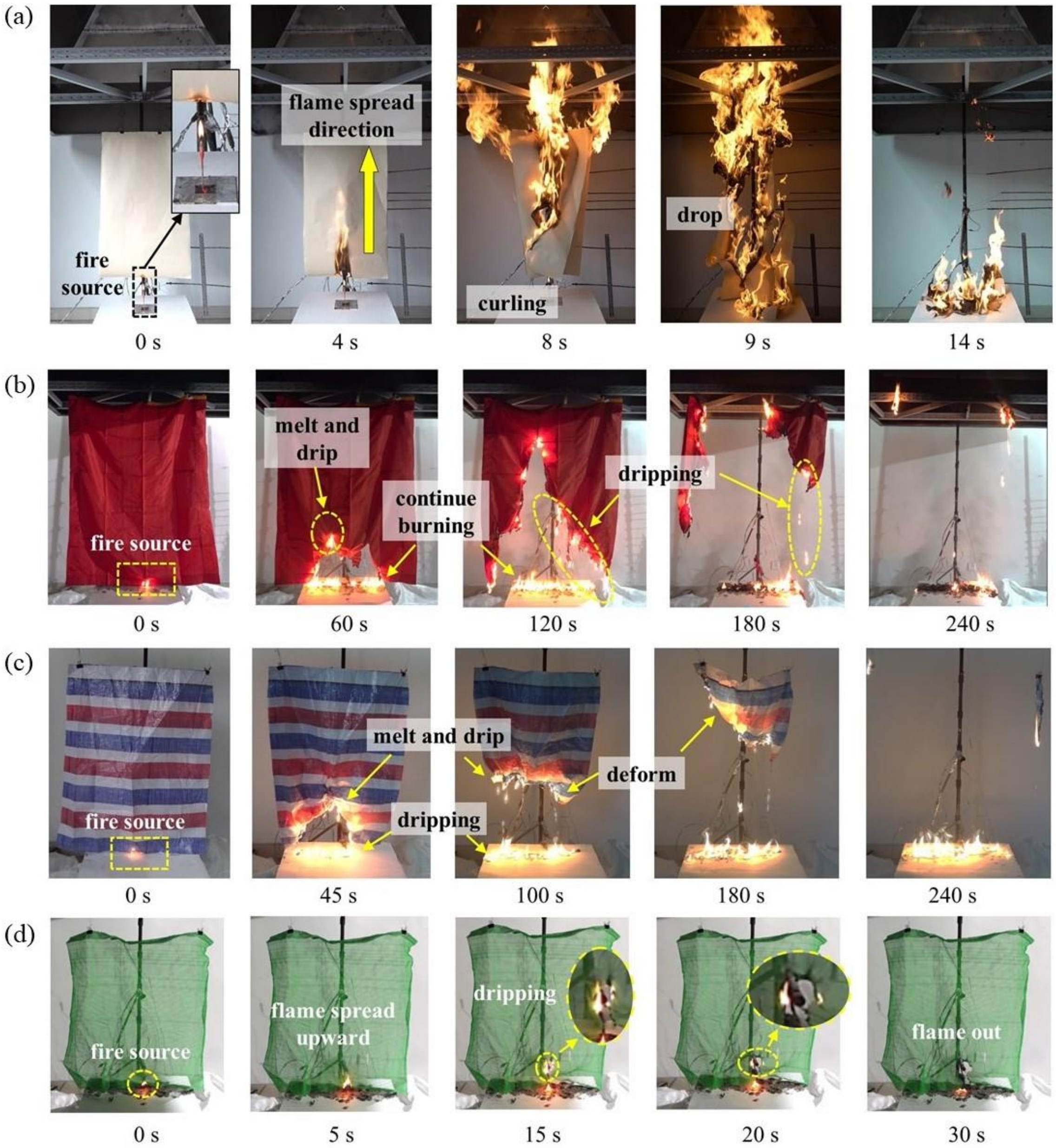

Fig. 7. Flame spread behaviors during the full-scale test. (a) Material-1, rice paper.(b) Material-8, clothes-1.(c) Material-11, rainproof cloth. (d) Material-12, nylon netting.

For the silk (Material-4), as the fire source approached, the region contacting with the fire can catch fire quickly, while the flame was hard to further spread. This phenomenon is in accordance with the above sections, which shows that this type of material is hard to sustain flame spread when exposed to the fire. For the synthetic fabrics used as clothes or decorations (Material-5 to 10), consistent with the standard vertical burning test, they were easy to burn and melt, and the flame spreaded with a large amount of dripping. Take Material-8 as an example, the ignition process occurred quickly, as shown at 0 s in Fig. 7(b). As the time went by, the burning area extended, and this type of material underwent melt. The burning part may detach from the sample to inhibit the upward flame spread somewhere, while other regions can continue to burn, as shown at 60 s, 120 s and 180 s. After dropping to the ground, the dripping with some unburned parts near the fire source continued to burn(as from 60 s to 180 s), until the complete extinguishment. Compared with vertical burning test, for large-sized material, flame will spread quickly and randomly, and the burning zone can extend both vertically and horizontally. As the burning and dripping have large randomness, it may explain why flame can sustain and burnout can occur only in the large-scale test for Material-9 and 10. Compared with Material-1 to 3 in Table 4, the synthetic fabrics have lower peak HRRs, while they can burn for a longer time, and their THRs can be higher.

For Material-11 and 12, they also revealed different burning behaviours compared to the small-sized samples. Different from the burning phenomenon in the above section, Material-11, which only burned partially in the vertical burning test, can maintain combustion until it totally burned out. As shown in Fig. 7(c), at the initial stage, burning process for Material-11 in the horizontal direction was much faster than in the vertical direction, and there was large deformation for this material. By this way, the flame spread also had a high randomness, as shown at 45 s, 100 s and 180 s. For another material, nylon netting, as shown in Fig. 7 (d), its sparse structure and the large heat loss to the surroundings inhibit the flame spread, leaving a large unburned area and a much lower HRR, which is in consist with the result of standard vertical burning test.

To better understand the burning process during the full-scale test, combustion parameters for some typical materials are shown in Fig. 8, including the HRR, the temperature distribution, and the radiation. Take Material-1, 8, 11 and 12 as examples. For HRR, as mentioned above, the value of natural fibre was higher than most of the synthetics, while the duration time of HRR is shorter, as shown in Fig. 8(a).

The temperature distributions both on the sample surface and near the sample are shown in Fig. 8(b) and(c). They all reveal large fluctuations, which can be explained with their burning behaviours. For rice paper (Material-1), during the burning process, as the flame climbed up along the sample, the burned region ruptured from the centre, which led the sample to drop to the ground. This process was reflected by the surface temperatures: For the positions near the bottom of the sample, as shown in Fig. 8(b), with the quick flame spread, their temperatures reached a peak within 10 s after ignition. As the flame spreaded upward, temperature near the surface raised subsequently. Once the thermocouples were covered with fire, the peak temperature can be around 600 °C. For the surroundings, as shown in Fig. 8(c), the location 10 cm away from the sample also had a peak of above 100 °C.

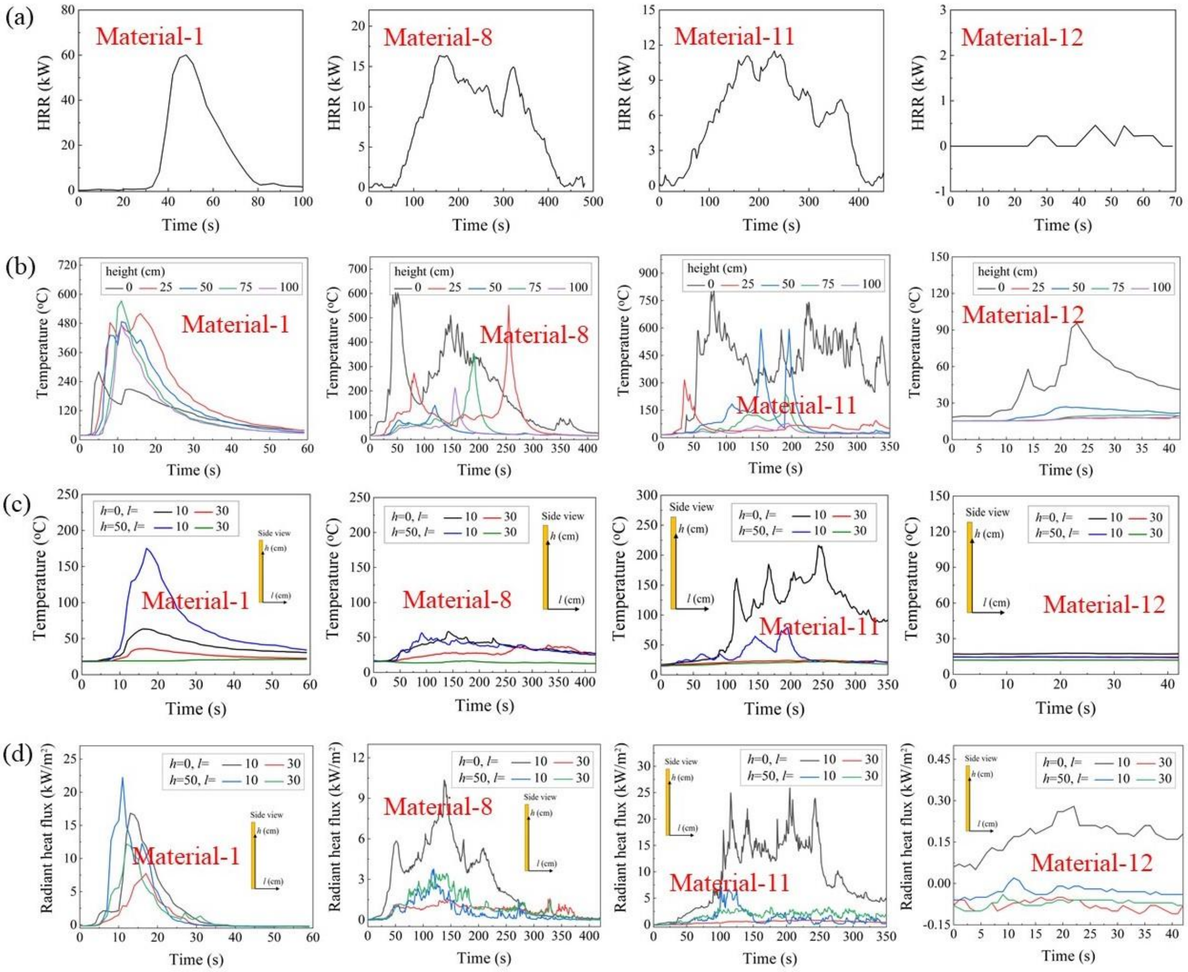

Fig. 8. Burning parameters for Material-1, 8, 11 and 12 during full-scale tests. (a) HRR, (b) Temperatures on the sample surface, (c) Temperatures near the sample, and (d) Radiant heat flux near sample.

Corresponding to the temperature, the burning sample provided large radiation up to 25 kW/m^2, as shown in Fig. 8 (d), which may cause damage to cultural relics. For the polymers, as they underwent dripping, their temperature distributions were more complex. As shown in Fig. 8, for Material-8 and 11, the dripping of the burning part led to large fluctuations of HRR, temperature and radiant heat flux. The highest temperature was around 600 °C for Material-8, and 750 °C for Material-11, and the surroundings 10 cm away from the sample can raise to over 200 °C. With the continuous dripping, there were more than one peak for the positions near the ground. The peak HRR was lower than 20 kW, but the duration time of the combustion process was longer compared to Material-1. Besides, for Material-12, as nylon netting was only partially burned, it did not show obvious regularity, and both the peak temperature and HRR were relatively low compared with other materials.

To further address the role of the dripping, we investigate typical dripping phenomenon for Material-5 and 6, as shown in Fig. 9(a). Material-5 was initially suspended in a linear shape, and

Material-6 was initially suspended in a hollow cylindrical shape. Once falling to the ground, the stacked form of the dripping residue was in line with the hanging structure, as a line for Material-5, and a ring for Material-6. It can be seen that after dropping, the residue can continue burning and smoldering. To study the effect of this phenomenon, we conducted an ignition test. As shown in Fig. 9(b), before the test, we put a pillow under the Material-5, and the pillow acted as a combustible. Once the Material-5 was ignited, it burned, melted and the dripping occurred, as shown at 40 s in Fig. 9(b). As the dripping parts still carried the flame, they can act as another fire source to ignite the pillow under it, and lead to the extension of the fire to the surroundings, as shown at 180 s with thicker smokes. The change of HRR with time is also shown in Fig. 9(b). For Material-5, its peak HRR was only 18.5 kW, while with other combustibles, the burning process can reach another peak of around 80 kW, which reveals a huge threat to fire safety, and may worsen the fire accidents.

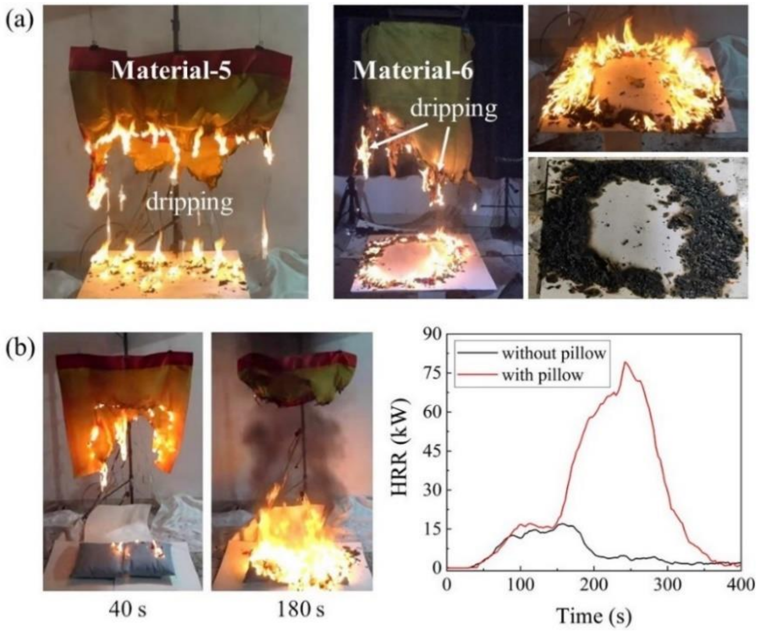

Fig. 9. Dripping characteristics during the full-scale test. (a) Typical dripping phenomenon for two shapes of hanging ornaments, and (b) Threat of the dripping flame for Material-5.

3.4. Summary of fire hazards for different materials in Chinese historical buildings

By conducting the FPA test, standard vertical burning test and full-scale test, an overall knowledge of the flammability and fire risks of different materials commonly used in Chinese historical buildings was obtained, which are shown and compared in Table 5. This table reveals a general trend of fire risks for each material. The rank of ignitability is based on FPA test, where the ignition time within 200 s can be regarded as easy to be ignited with the continuous O_2 supply and a pilot, and the time larger than 500 s is hard to be ignited. The material whose THR/HRR much larger than average range in both FPA test and full-scale test has a higher rank of heat release. Upward flame spread trend stands for the trend of fire development after the ignitor is moved away, which is obtained by standard vertical burning test and full-scale test. And damage degree means the ratio of the burning part.

Table 5. Summary of fire hazards for different materials.

	Material	Ignitability	Heat release	Upward flame spread trend	Dripping	Damage degree
1	Rice paper	Medium	High	High	Low	High
2	Cotton cloth	Easy	High	High	Low	High
3	Kraft paper	Easy	High	High	Low	High
4	Silk scarf	Hard	Low	Low	Low	Medium
5	Ornament-1	Medium	High	High	High	High
6	Ornament-2	Medium	High	High	High	High
7	Pennant	Medium	Medium	High	Medium	High
8	Clothes-1	Medium	High	High	High	High
9	Clothes-2	Medium	High	Medium	High	High
10	Clothes-3	Hard	High	Medium	High	High
11	Rainproof cloth	Medium	High	Medium	High	High
12	Nylon netting	Medium	Medium	Low	Medium	Medium

From this table, it shows that for natural fibre-based materials, in general, they are easy to be ignited and have high heat release. The flame tends to spread on this material quickly and spontaneously, leading to a relatively high damage degree. For the silk cloth, it is hard to be ignited by external heat flux, while it can burn with the contact of open flame, which means it is liable to have local damage as well. For synthetics, the burning behaviours vary among different materials and show some randomness, which is due to its gradients, textures, and dripping characteristics. During the burning process, most of polymers are easy to melt and drop, which can carry flames to the ground. Dripping has two main effect on the burning process, the first one is that it can detach from the burning material and inhibit further spread of the fire on the material surface, while the second one is that the dripping part may ignite other combustibles, which is adverse for the protection of culture relics and antiques. Therefore, most of the synthetics have a high fire hazard, except for nylon netting (Material-12), which is too sparse to sustain the flame spread process.

4. Conclusions

In this work, common combustible materials in Chinese historical buildings are studied, which are made of different kinds of ingredients, such as natural plant fibre, protein, and chemical composite. By conducting FPA test, standard vertical burning test and full-scale test, the dynamic burning behaviour was analysed, and the combustion characteristics under the real size of these materials was investigated. By this way, a better understanding of their flammability and fire spread behaviours is obtained as follows:

For the natural fibre-based materials, such as paper and cotton cloth, they are easy to be ignited, undergo flame spread with the rapid increase of HRR and combustion products, and burn out within a short time. As this material is soft, the combustion process is accompanied by the deformation and curling, which contributes to fluctuations of the temperature, HRR and MLR.

For the textile made of protein, such as silk, the typical parameters, such as HRR, MLR, CO_2P, etc., reveal much lower values and variations during the whole test. With external heating, the material can be easily charred, while there is no obvious flame spread trend during the burning process. However, this material can also be ignited by open flame, which should be kept far away from fire sources, such as candles and incense burners.

For the synthetics, their texture, ingredients and other factors will affect the flame spread behaviour. The most important combustion characteristics is that the flame will propagate accompanied by dripping. For some materials, their melting speed is faster than fire spread rate, which inhibits the fire spread. However, due to the high temperature of the dripping with flames, this material is liable to ignite the surrounding combustibles, which may extend the flame spread area and cause damage to antiques and cultural relics. Therefore, sufficient cautions should be taken for this fire hazard.

Acknowledgements

This work was supported by the National Key Research and Development Plan of China (No. 2020YFC1522800) and the National Natural Science Foundation of China (NSFC) (No. 51976211).

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