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Influence of air-gap and thickness on the upward flame spread over discrete wood chips

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ABSTRACT

The fire hazard has frequently destroyed wooden cultural heritages. The discrete wood chips allow fire propagation quickly in practice. This study aims to clarify the effect of air–gap and thickness of wood chips in the fire propagation mechanism by experimental investigating the mass loss rate (MLR), flame spread rate (FSR), total burning duration (TBD) and the flame characteristic length (MFL). The 2 cm long and 10 cm wide wood chips were uniformly installed on a vertical sample holder. The air–gap distance and the thickness of wood chips changed from 1.0 cm to 3.0 cm and 1 mm to 4 mm, respectively. The flame spreads across with the wood grain orientation. The experimental result shows that FSR and MFL are sensitive to the air–gap distance. It is concluded that, TBD versus thickness of the sample is linear with an equation TBD (s) = 7.7 × thickness (mm) + 18.6. Concerning the fixed thickness of the sample, the TBD varies a little from the air–gap distance. The MFL increases to a peak then decreases to a low value as the thickness differing from 1 mm to 4 mm. It is observed that the air–gap makes little contribution to the TBD. The MLF history as the air–gap distance changing from 1.0 cm to 3.0 cm indicates that the distance of air–gap imposed little effect on the MFL. The a-MLR profiles mainly depend on the thickness of the sample.

Introduction

Chinese cultural heritage is mainly characterized by wooden historical buildings [1]. It is a non-renewable cultural heritage and a carrier of civilization of past Chinese times. In addition to the architectural and tourism value, the potential historical and cultural values are precious. It is a pity that many historical buildings had been destroyed due to the ravages of fire disasters worldwide [2]. For historic wooden buildings located in Asia, fire protection is the main emphasis of current work. One typical fire case is the Shuri castle, which happened on the 31st of October 2019 (see Fig. 1). The flame spread was observed too fast to be difficult for fire-fighter. Many historic buildings in the long historical process have been kept in China since it is an ancient country of historical civilization [3]. The lesson learned from the Shuri castle fire indicates that a deep understanding of fire spread over similar wooden structures is necessary since Chinese historic buildings are similar to Japan. Usually, vertical fire spread over wooden beam is more hazardous in fire safety. The air–gap between two beams imposes an influence on the fire spread rate. In the previous study, the fire spreading performance over discrete weathered wood chips has been reported. The primarily conclusion indicated that both air–gap and thickness showed a significant effect on the fire spread according to the results of two tests [4]. Although flame spread over discrete fuel has been reported to be more comprehensive and hazardous in fire safety, it is still a topic for fire researchers. Until now, a comprehensive understanding of air–gap and thickness influence on the fire spread over discrete wood chips had not been achieved yet.

Several available approaches have been developed in the literature to address the fire spread over discrete woods. The previous researchers investigated the burning behavior of vertical matchstick arrays [5], the flame spread over discrete [6], the criterion of flame spread over single-row birch rods [7], the fire spread of wooden dowels [8], the influence of gap size on the flame spread [9], the inclination angle on concurrent flame spread over discrete fuel arrays [10], the fire spread within a

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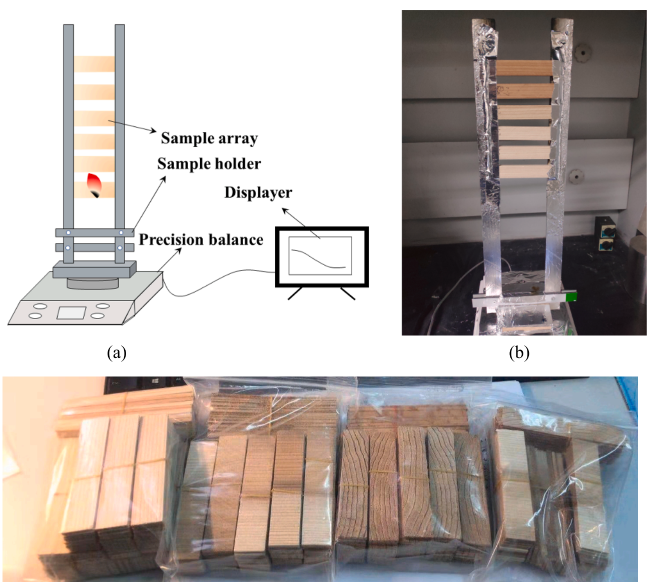
(a) (b)

Fig. 1. The description of wooden historic building fire (a) The Shuri castle fire in Japan (http://www.cepnews.com.cn/news/guoji/62452.html) (b) A temple fire in China (https://www.sohu.com/a/209980703_661262).



(a) (b)

(c)

Fig. 2. Experimental apparatus description. (a) The front view image. (b) The side-view schematics. (c) Wooden samples.

group of model houses [11], and so on. In general, most of the available works provided a preliminary conclusion that air-gaps could increase the flame spread rate and the solid burning rate. However, a comprehensive understanding of fire spread over woods discrete chips is still needed since relative knowledge are lacking.

Therefore, in the current contribution, to achieve a detailed understanding of air–gap and thickness influence on the flame spread performance, a series of tests are conducted to obtain the burning duration, MLR, peak of MLR, flame spread rate, and flame length varying sample of thickness and air gap distance. Then the resultant data is discussed and reported. It hopes to provide a potential understanding of the flame spread over the wooden structure.

Experiment and method

Flame spread measurement test

The experimental apparatus was described as shown in Fig. 2. The measurement facility generally consists of a high precision balance, a self-made sample holder, data collection equipment, a camera, and a hood for fire tests. Six wood chips are fixed in a sample holder. The length of the sample is 2 cm, and the width of the sample is 10 cm. The detailed information of the wood sample could be obtained from our previous work [12]. During the tests, two-sample holders are installed to keep the flame spread vertically. Then, duplicate tests were carried out. For fixing the wood chips firmly on the holder, two layers of alumina tape were used to avoid the dropping of samples. The average distance between the two holders is about 7.0 cm. The balance is employed to record the MLR and the peak of MLR, which has a 0.001 g resolution and 20 Hz frequency. After the bottom wood chip is ignited by a lighter and lasting for 3 s, a camera (Canon Rebel T3i 1080P) is used to record the base position images at 30 frames per second with a spatial resolution of 0.47 mm/pixel. The hood is without ventilation, and the ambient temperature and moisture are 23–32 ℃ and 25–45 %, respectively.

The test conditions are shown in Table 1. The sample thickness changes from 1 mm to 4 mm, air–gap distance varies from 1 cm to 3 cm. The total burning duration (TBD) time is calculated according to the test video, which is a typical method as shown in the reference [6]. It is defined that the time between the onset of preheating (start time) and ending of total fuel (end time) is TBD. To avoid the uncertainty from the observation of flame spread, both the repeated MLR and flame spread profiles are compared to determine the start and end times. Flame spread rate (FSR) is obtained by utilizing the flame top and its corresponding time. For a wooden structure, the flame spread rate is an important index. In the current work, FSR is obtained by an image treatment method. The MATLAB code is developed and used. The flame intensity over the k-th fuel segment was defined as [13] :

$$I_k^* = \frac{\sum_i^I \sum_j^J R(i,j)}{255 \times I \times J}$$

Here, k ranges from 1 to 6, with 1 indicating the bottommost fuel segment and 6 representing the uppermost fuel segment. R (i, j) means the red value of an RGB image at a pixel located (i, j). R differs from 0 to 255. I and J are the total pixels in the width and length of each sample segment.

Mass loss profile could be a characteristic parameter for special materials. When the wood chips are exposed to a flame, the mass-loss rate (MLR) is an index for flame spread. The average MLR (a-MLR) value is obtained based on averaged mass-loss rate during the flame existing time. In addition to a-MLR, the peak value of MLR (p-MLR) is also a key parameter for flame spread, which is obtained based on the curves of MLR. Maximum flame length (MFL) is defined as the part between the top and the bottom of the flame, which is used to evaluate the risk for a big fire [14,15]. When the MFL is large, fire risk is high under this condition since the big MFL makes a big contribution to a whole fire. According to the previous study [4], the uncertainty analysis of similar tests has been discussed and could be accepted by the duplicate test. All the data summarized and shown in Table 1 are the TBD (s), a-MLR (g/s), p-MLR (s), p-MLR (g/s), FSR (mm/s) and MFL (mm) for each test, respectively.

Results and discussion

The description of flame spread observation

In the previous study, the air–gap and thickness of samples have been found to impact the flame spread over discrete fuels significantly. However, a comprehensive and systemic investigation is absent. In

Table 1
The test condition and results of flame spread measurement tests.

Test No.	Sample thickness (mm)	Air-gap size (cm)	Total burning duration (s)	Flame spread rate (mm/s)	Maximum flame length (mm)	Average MLR(g/s)	Peak MLR (g/s)
1	1	1	21	12.28	618.32	0.106	0.249
2	1	1.5	23	14.85	628.99	0.116	0.231
3	1	2	27	17.07	624.87	0.105	0.257
4	1	2.5	25	19.66	670.29	0.115	0.273
5	1	3	27	21.85	695.38	0.114	0.264
6	2	1	52	6.46	692.59	0.093	0.231
7	2	1.5	40.5	9.32	654.97	0.116	0.275
8	2	2	44	10.23	682.84	0.106	0.257
9	2	2.5	49	11.49	710.71	0.101	0.242
10	2	3	41	12.08	557.63	0.109	0.246
11	3	1	62.5	4.00	650.79	0.108	0.24
12	3	1.5	65.2	5.38	645.21	0.124	0.266
13	3	2	77.5	6.5	585.29	0.101	0.219
14	3	2.5	68.5	6.64	647.04	0.104	0.245
15	3	3	67	7.51	508.50	0.111	0.209
16	4	1	77.5	3.58	515.54	0.087	0.180
17	4	1.5	80	4.56	521.18	0.101	0.232
18	4	2	74.5	4.75	538.95	0.110	0.237
19	4	2.5	78.5	5.24	422.96	0.105	0.221
20	4	3	85	6.06	473.46	0.099	0.218

addition to the traditional FSR parameter, the TBD, MLR, and MFL also are detailed in the following content. To describe the flame spread performance, the front-view images of flame spread over discrete wood chips (thickness = 2 mm) with varied air–gap distance are illustrated in Fig. 3. The air–gap changed from 1 cm to 3 cm. For a flame spread over discrete solid fuels, FSR and MFL were observed to be sensitive to the distance of air–gap. The FSR and MFL could be accelerated because of sufficient air comes from the air–gap, which results in a whole fire. However, the FSR and MFL are also reduced due to the discontinuity of flame. Once the flame is separated, the FSR would be decreased soon. The final smouldering for a short time during a test is ignored because it does not contributes to the performance of flame spread.

The comparison of flame behaviours at t = 10 s indicates that flame spread are accelerated at the beginning stage of the test, just as shown in Fig. 3 (t = 10 s). When the time approaches t = 25 s, the flame nearly was observed to reach a maximum length. Then the flame length decreased due to the inefficient pyrolysis gas which comes from the bottom supply. When the diffusion of pyrolysis gas is affected by the flame spread, the flame is unstable. It is found that as the distance of air–gap increases, the flame becomes fluctuant. The flame of test condition air-gaps = 3 cm, and t = 30 s is discontinued, just as discussed above. For a big wooden structure, the flame spreading with the violent flow of pyrolysis gas is considered conducive to a whole fire. The pyrolysis gas production rate depends partly on the thickness of the sample. Wood chips can easily be carbonised due to incomplete combustion [16]. When the sample is thin, the pyrolysis process is completed. In contrast, the coating carbon layer would decrease heat transfer from the surface to the wood interior, resulting in a decrease in production rate of pyrolysis gas [17]. Therefore, the influence of air–gap and thickness of on the wood sample the flame spreading are mainly by the process of pyrolysis gas production and gas flow. The detailed discussion is shown in the following content.

The influence of thickness of sample on the flame spread performance

The thickness of the wood sample shows a clear influence on the production rate of pyrolysis gas. The descriptions of TBD, FSR, MFL, a-MLR and p-MLR are listed in Fig. 4 **(a)**, Fig. 4 **(b)**, Fig. 4 **(c)**, Fig. 4 **(d)** and Fig. 4 **(e)**, respectively. In general, the flame spreading is greatly affected by the thickness of the samples [18].

The burning duration time is linear with the thickness of the sample, just as shown in Fig. 4 **(a)**. The air–gap distance shows little influence on the TBD. The averaged TBD of thickness 1 mm, 2 mm, 3 mm, and 4 mm for 5 types of air–gap are 24.6 s, 45.3 s, 68.1 s, and 79.1 s, respectively. The BTD versus thickness of the sample is linear by an equation TBD (s) = 7.7 × thickness (mm) + 18.6 (R^2 = 0.99). It could be used to predict the burning duration before a test. Regarding the fixed thickness of the sample, the TBD varies from an air–gap distance, which would be discussed in the below part. Therefore, the pyrolysis gas production rate is inferred to be the main controlling factor for the burning duration. For a wooden structure, fire load is a key index.

Fig. 4 **(b)** shows the result of the FSR varying thickness of the sample. In general, it indicates that when the thickness of the sample increases from 1 mm to 4 mm, the FSR is reduced significantly. The air–gap is found to be conducive to the acceleration of FSR for a fixed thickness. The FSR is mainly increased for a thin sample (thickness = 1 mm or thickness = 2 mm) as the air–gap changes from 1 cm to 3 cm. When the thickness of the sample become thick, the acceleration of FSR is not apparent. It may be due to the low pyrolysis gas production rate caused by the coating effect of carbon during the wood pyrolysis process. Exception for cases performed with the thickness of 1 mm, the thickness differing from 2 mm to 4 mm is linear with averaged flame spread rate. It has a relationship with the combustion style change of thermal-thick to -thin when the sample becomes thin gradually [5].

The flame length is defined as the length between flame-base and flame-tip during the test. The steady flame length varying thickness of samples is summarised in Fig. 4 **(d)**. The system deviations of tests effects on the MLF were reported in our previous work. It is found to be acceptable and accurate [19]. MFL is essential for the evaluation of fire risk. A big MLF indicates a high risk for fire spreading over the wooden structure for a fixed condition. Exception for the case performed with air–gap = 3 cm, the MFL presents a rule that it increases to the peak then decreases to a low value as the thickness of sample differs from 1 mm to 4 mm. In contrast, the MFL of cases with a 3 cm air–gap is generally reduced by the increase of thickness of the sample from 1 mm to 4 mm. It is because the increase of air–gap distance reduces the discontinuity of flame. Therefore, to achieve a small MFL, the optimal air–gap should be used.

The MLR during fire spreading over discrete wood chips presents potential information for pyrolysis gas production rate. The results of MLR are summarized in Fig. 4 **(d)** and Fig. 4 **(e)**. The p-MLR is also a characteristic factor for each condition. Both a-MLR and p-MLR are affected by the thickness of the samples. For a-MLR curves, it increases from an initial value of each test to a peak then comes down to a low MLR. The peak of a-MLR is found at the thickness of sample = 3 mm commonly. Regarding the p-MLR of tests, the exception case is found in the case performed with air–gap = 1.5 cm. In contrast, nearly all the p-MLR of tests are reduced as the thickness of the sample differing from 1

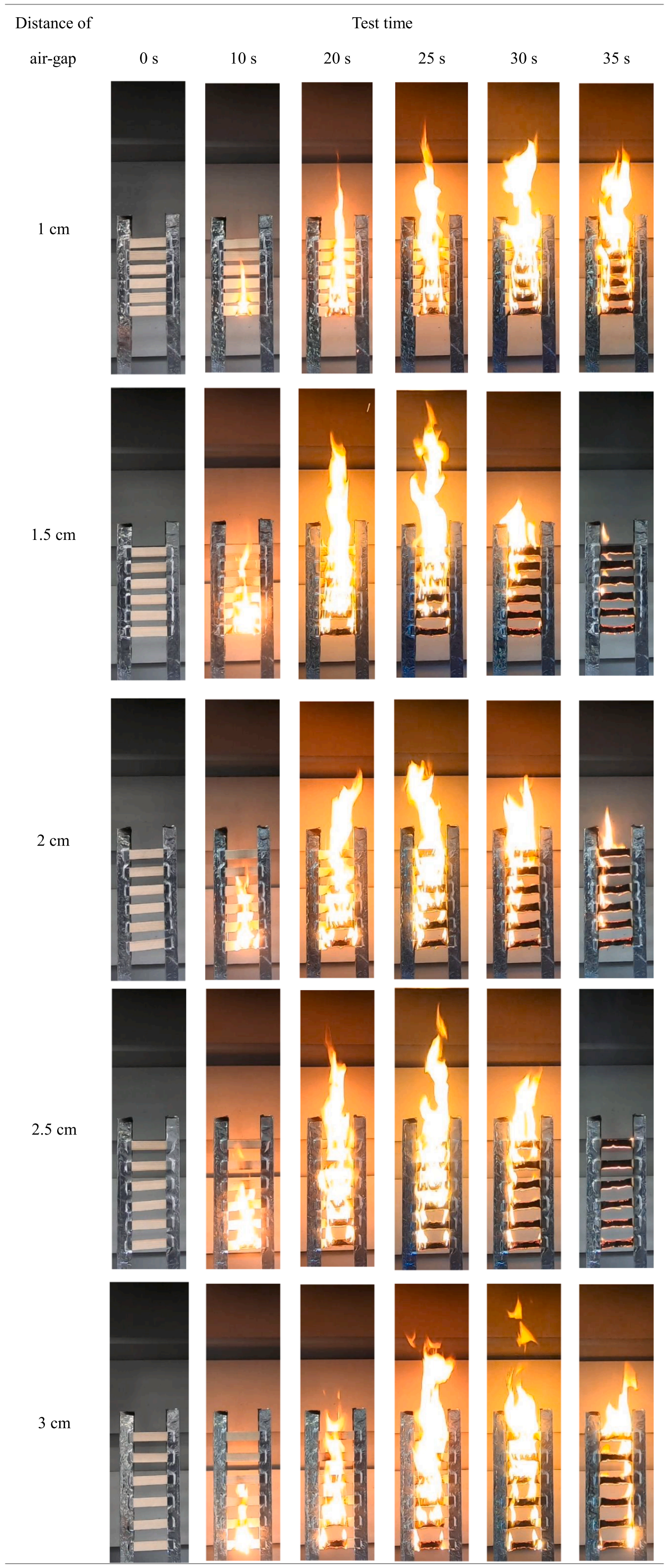


Fig. 3. The front-view images of flame spread over discrete fuels with varied distance of air–gap when the thickness of sample = 2 mm.

mm to 4 mm. This is consistent with it that a high charring rate would decrease the pyrolysis during the wood fire [20]. Based on the analysis of the above content, it is found that the thickness of the sample showed a big influence on the FSR and TBD due to the increase of pyrolysis gas production rate.

The distance of air–gap influence on the flame spread performance

When the flame spread over discrete wood chips, the air–gap distance is found to play an important role in the gas flow and continuity of a flame. In the following content, attempts to clarify air-gaps on the flame spreading are detailed. For discrete solid fuels configuration, the below equation has been reported to present a flame spread rate for each

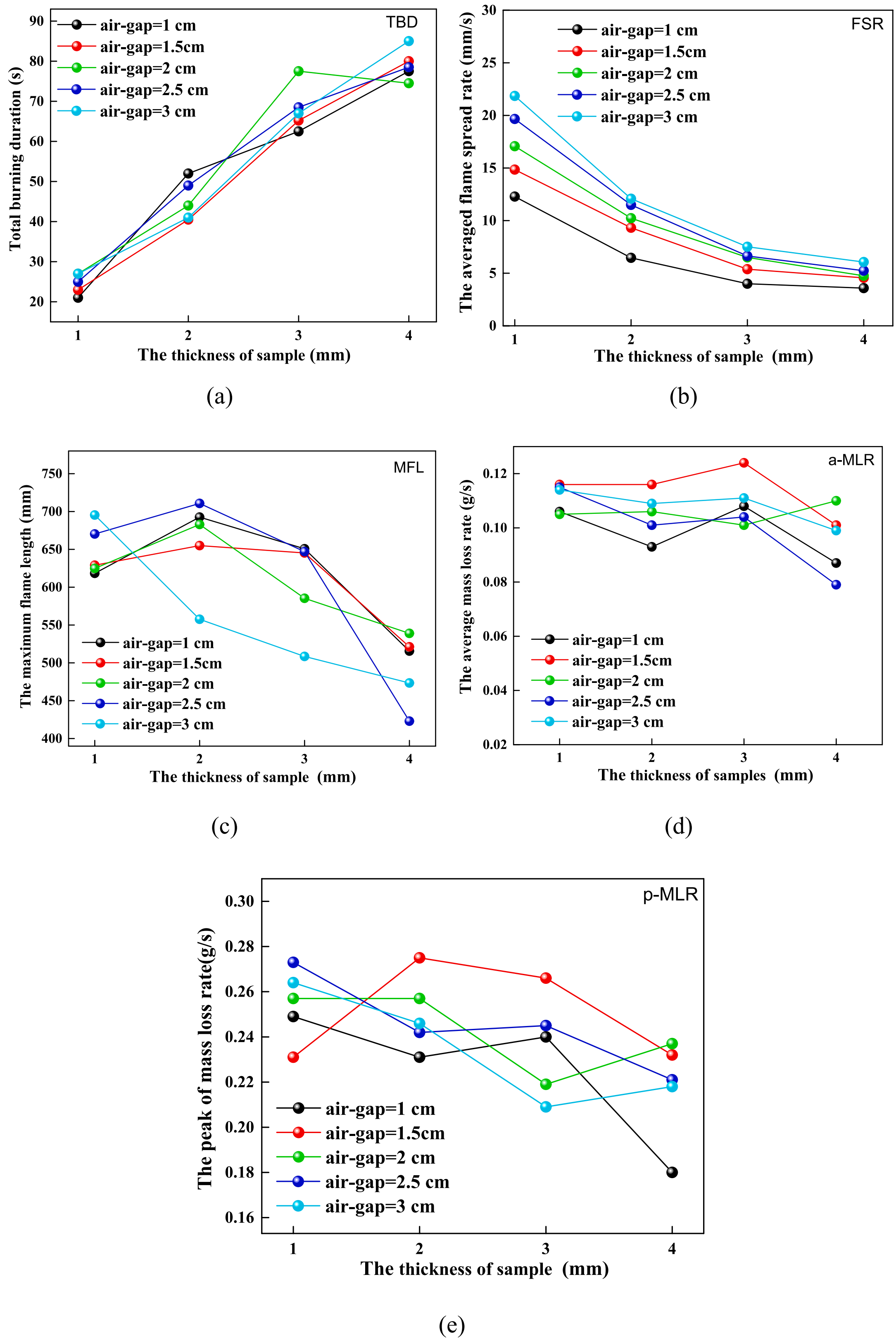


Fig. 4. The description of the TBD, FSR, MFL, a-MLR and p-MLR differing thickness of samples (a) TBD (b) FSR (c) MFL (d) a-MLR (e) p-MLR.

sample arrangement [13]: $V_{flame} = (L_{gap} + L_{fuel})\left(\frac{d(\text{start time})}{d(\text{number of fuel})}\right)^{-1}$. Where L_{gap} and L_{fuel} are defined as air gap size and the vertical span of each sample, respectively. Then the following equation is obtained: $V_{flame} = \frac{\dot{q}_f''(f)f\delta_f}{\rho d c_p (T_p - T_\infty)}$. Here $f\rho d$ is defined as apparent area density, $\dot{q}_f''(f)$ indicates the incident heat flux, which is a function of fuel percentage. Fuel percentage is $f = \frac{L_{fuel}}{L_{gap}+L_{fuel}}$, and $f\delta_f$ is acted as an effective sample preheat length. It is clear that the flame spread rate is a variation of the

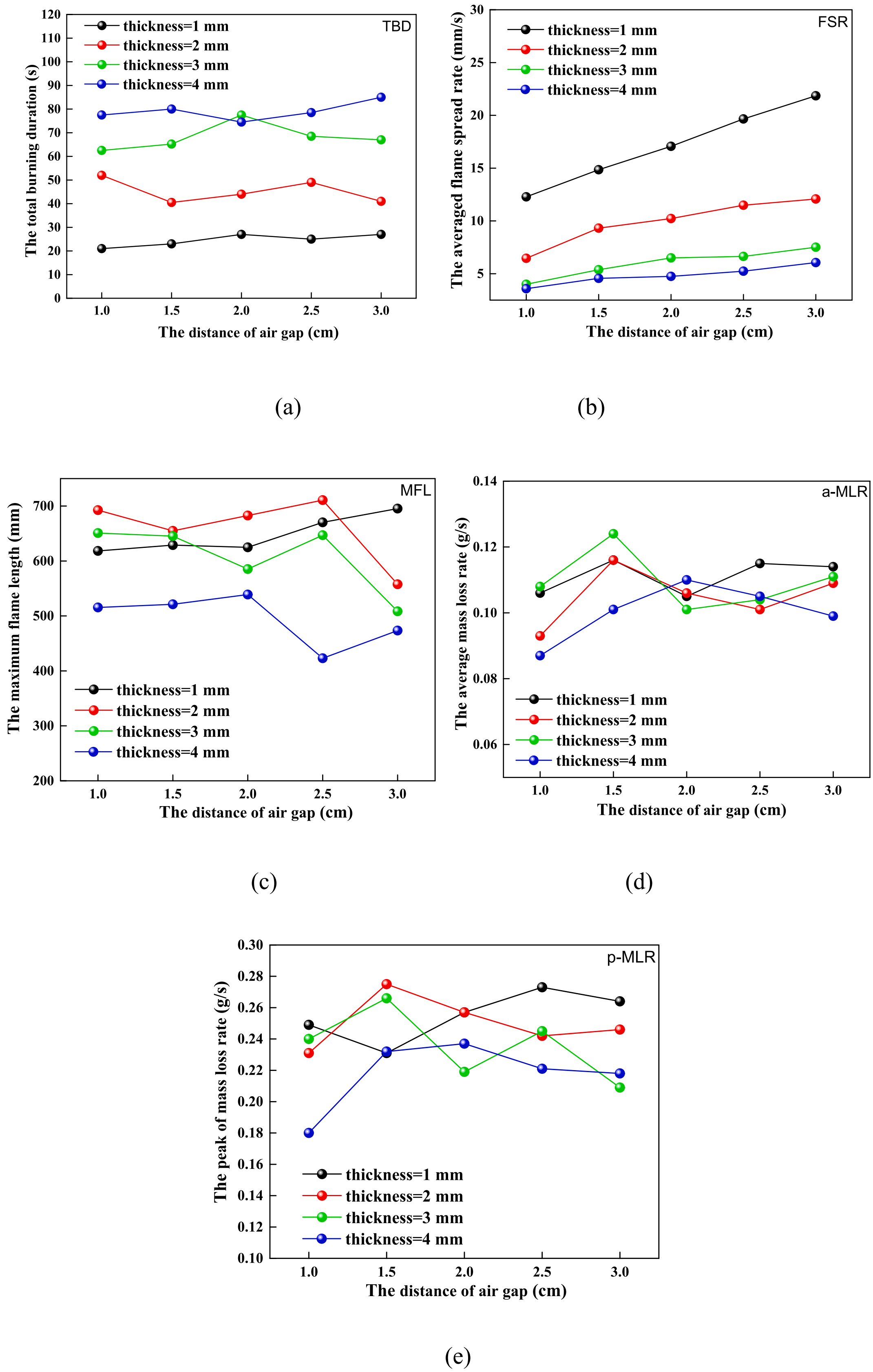


Fig. 5. The description of the TBD, FSR, MFL, a-MLR and p-MLR varying air–gap distance (a) TBD (b) FSR (c) MFL (d) a-MLR (e) p-MLR.

solid fuel percentage due to air–gap distance. This could be well explained by it that the distance of the air–gap could reduce sample preheating length, flame standoff distance, and sample fuel load, respectively [21]. Considering the flame spreading mechanism that the flame-base moves upwards over the sample span and air gap, a dominant factor among the above three factors differs from test configurations.

Fig. 5 **(a)** shows a TBD profile varying the air–gap distance from 1 cm to 3 cm. It is observed that the air–gap makes a little contribution to TBD. Concerning a fixed air–gap distance, the TBD depends on the thickness of the sample. This is in part due to the fixed pyrolysis gas rate. Once the thickness of the sample is fixed, the TBD could be simply evaluated. Regarding the FSR varying the air–gap distance (just as shown in Fig. 5 **(b)**), the FSR increases as the air-gaps change from 1 cm to 3 cm. The air–gap distance imposed a significant effect on a thin sample. It is partly due to the lack of sample preheating length and inadequate supply of flame standoff distance. For the former, it leads to a low pyrolysis gas production rate. The inadequate supply of flame would result in a discontinuity of flame spread. The flame may stop if the air-gaps are large enough (the fuel load is too small). The FSR of cases for thickness of sample approaching 1 mm, 2 mm, 3 mm and 4 mm could be predicted by FSR (mm/s) = 7.56 × air–gap (cm) + 4.79 (R^2 = 0.99), FSR (mm/s) = 4.55 × air–gap (cm) + 2.68 (R^2 = 0.90), FSR (mm/s) = 2.69 × air–gap (cm) + 1.13 (R^2 = 0.90) and FSR (mm/s) = 2.58 × air–gap (cm) + 1.13 (R^2 = 0.94), respectively. The MLF history versus air–gap distance from 1.0 cm to 3.0 cm is illustrated in Fig. 5 **(c)**. It indicates that the air–gap distance imposed little effect on the MFL when it varies from 1 cm to 3 cm. It is inferred to be relative to sufficient supply of preheating length and standoff flame. As the air–gap distance approaches 3 cm, the discontinuity of flame is obvious. In addition, there is a small peak on the curve of MFL versus air–gap distance when the thickness of the sample changes from 1 mm to 4 mm. It is found that as the thickness of the sample increases, the peak approaches a small air–gap. It means that for a thick sample, the peak of MFL curves would appear when the air–gap distance is small.

Fig. 5 **(d)** and Fig. 5 **(e)** illustrate a-MLR and p-MLR, respectively. Fig. 4 (d) indicates that air–gap distance imposed little influence on the a-MLR during fire spread tests. The a-MLR profiles depend on the thickness of the sample mainly. The air–gap distance makes no contribution to the pyrolysis of wood chips. The air–gap is relative to the preheating length and flame standoff, but the effect is minimal if the air–gap is smaller than 3 cm. Compared with a-MLR, the p-MLR shows a big range of variation from 0.18 g/s to 0.28 g/s. It suggests that when the thickness of the sample approaches 4 mm, the p-MLR is reduced largely compared with the thickness of 1 mm as the coating carbon reducing the pyrolysis process.

Conclusion

In this work, a series of tests were conducted to have a deep understanding of air–gap distance and thickness of sample influence on the flame spreading performance over discrete solid wooden chips. During the tests, the air–gap and the thickness of samples changed from 1 cm to 3 cm and 1 mm to 4 mm, respectively. Based on the above experimental results and detailed discussion, the following conclusions are obtained:

(1). The experimental results show that FSR and MFL are sensitive to the air–gap distance for a flame spread over discrete solid fuels. The FSR and MFL could be accelerated because enough air comes from the air–gap, which results in a whole fire. However, the FSR and MFL also be reduced due to the discontinuity of flame.

(2). In the discussion of the influence of thickness on fire spread performance, it is found that BTD versus thickness of the sample is linear by an equation TBD (s) = 7.7 × thickness (mm) + 18.6. Concerning the fixed thickness of the sample, the TBD varies a little from the air–gap distance.

(3). Regarding the FSR, the acceleration of FSR is not so noticeable when the thickness of the sample approaching a thick sample. It may be due to the low pyrolysis gas production rate caused by the coating effect of carbon during the wood pyrolysis process.

(4). For the MFL, it increases to a peak then decreases to a low value as the thickness of the sample differs from 1 mm to 4 mm. It could be due to the discontinuity of flame, which is reduced by increasing air–gap distance. The FSR of tests when the thickness approaching 1 mm, 2 mm, 3 mm and 4 mm could be calculated by FSR (mm/s) = 7.56 × air–gap (cm) + 4.79 (R^2 = 0.99), FSR (mm/s) = 4.55 × air–gap (cm) + 2.68 (R^2 = 0.90), FSR (mm/s) = 2.69 × air–gap (cm) + 1.13 (R^2 = 0.90) and FSR (mm/s) = 2.58 × air–gap (cm) + 1.13 (R^2 = 0.94), respectively.

(5). The MLF history with the air–gap distance changing from 1.0 cm to 3.0 cm indicates that the distance of air–gap imposed little effect on the MFL. For a thick sample, the peak of MFL curves would appear when the air–gap distance is small.

(6). Both a-MLR and p-MLR curves indicate that air–gap distance imposed little influence on the a-MLR during fire spread tests. The a-MLR profiles depend on the thickness of the sample mainly. However, the wood grain orientation for each denoting effect during fire spreading performance should be further studied.

CRediT authorship contribution statement

Biao Zhou: Conceptualization, Methodology, Writing – review & editing. **Kai Wang:** Conceptualization, Methodology, Writing – review & editing. **Min Xu:** Data curation, Writing – original draft. **Wangyu Yang:** Data curation, Writing – original draft. **Feng Zhu:** Investigation. **Biao Sun:** Investigation. **Xuan Wang:** Investigation, Validation. **Wei Ke:** Investigation, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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