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# Experimental Study of Upward Flame Spread over Discrete Weathered Wood Chips

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**ABSTRACT**

Wooden culture heritage has caused serious results due to the ravages of frequent fire disasters. The fire propagation over the weathered wood was reported to be fast, especially wood separated by air gaps. Presently, experiments were performed to study weathering effects on the flame spread performance over discrete wood chips separated by air gaps. A series of six 2 cm-long 10 cm-wide wood chips were uniformly installed on a vertical sample holder. The thickness of wood chips differed from 1 mm to 7 mm, the air gaps between the two samples varied from 1 cm to 2 cm. The flame spreads across or along with the woodgrain orientation. It indicates that the accelerated weathering process impacted a clear influence on flame spread over discrete wood chips. Regarding the flame spread across woodgrain orientation, both burning duration and MLR were reduced. In contrast, the burning duration was greatly enlarged but MLR was decreased when flame spread along with the woodgrain orientation. In general, the thickness differing from 3 mm to 7 mm was found to be linear with averaged flame spread rate. It suggests that the flame length of the samples with a horizontal grain orientation (flame across woodgrain) and vertical grain orientation (flame along with woodgrain) are increased and shorten greatly due to accelerated weathering, respectively.

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**KEYWORDS**
Discrete fuels; flame spread rate; MLR; weathered wood; wooden culture heritage

## 1. Introduction

As the carrier of civilization, historical buildings are a non-renewable cultural heritage. In addition to the architectural value and tourism value, the potential historical value and cultural value are precious (An and Wang 2016). Unfortunately, many of these buildings worldwide had been destroyed due to the ravages of fire disasters (Li et al. 2018; Zhou, Zhou, and Chao 2012; Zhou, Zhou, and Jin 2010b; Zhou, Zhou, and Xiang 2010a). Recently, historic building fire has taken place in Brazil (de Sa, Sa, and Lima 2018), France (Mackie and Sim 2019), Germany (Turner 2017), UK (Rawlinson and Gayle 2017), Japan, and so on. As an ancient country of historical civilization, China has retained many historic buildings in the long historical process (Yin and Yamamoto 2013). According to Chinese official statistics, 4291 historic buildings are recognized by the government during the past 50 years, from 1961 to 2015 (Wu, Zhang, and Zeng 2017). The damage of historic buildings by fire is devastating in China (Zhou et al. 2018). Compared with other countries, Chinese historic buildings are mainly characterized as wooden structures (columns or beams) which showed a high fire risk, especially after years of natural weathering. It is known to all that as time goes on, the wood was much easier to be ignited because of the serious deterioration (Zhou et al. 2018). The flame spread over the wood surface is complicated (Popescu and Pfriem 2020). And compared with continuous fuels, discrete fuel can be more hazardous in fire safety (Cui and Liao 2019). The presence of gaps can increase the flame spread rate (Gollner et al. 2012) and the solid burning rate (Park et al. 2018). While fire behavior and flame spread over continuous wood have been extensively studied with various configurations under a wide range of ambient conditions, a comprehensive understanding of fire spread over discrete weathered wood chips had not yet been achieved.

There have been many attempts in the literature to develop approaches that address the fire spread over continuous woods. The main emphasis of available fire spread over wood researches are focused on thickness effects on vertical fire spread (Meng et al.

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2018), effects of preheating on fire propagation (Lai et al. 2020), influence of external heat flux and ambient oxygen concentration (Wang et al. 2018), the influence of surface treatment (Gašpercová and Makovická Osvaldová), modification performance of wood impregnated with carbon nano-materials (Song et al. 2020), numerical simulations (Ren et al. 2017; Zeinali et al. 2019), fire retardants performance (Östman 2017), and so on. Although the fire spread of wooden dowels is reported (Jiang et al. 2019), the woodgrain orientation and weathering influence on the fire spread over discrete weathered woods is still unavailable. In general, most of the available works were just focused on the traditional wooden samples but not the weathered ones. However, the deep understanding of the weathering process effects on fire spread over weathered woods is of great necessity since a great many historic building was lost due to fire in China. Little knowledge about it is available now.

In this contribution, to achieve a detailed understanding of weathering process influence on the flame spread performance, a series of tests are conducted to discuss the burning duration, MLR, peak of MLR, flame spread rate, and flame length of discrete samples that are after and before weathering process. Authors detail works involving the burning duration varying weathered or traditional wood chips, explore MLR differing the woodgrain and air gap, discuss the flame spread rate changing the thickness of the sample and propose a potential explanation to understand the weathering process effects on the flame spread performance over discrete wood chips

## 2. Experiment and method

### 2.1. Flame spread measurement test

The experiment method was according to Figure 1. A series of wood chips are installed uniformly on a vertical sample holder. The sample materials are cedar. The physical information of cedar could be found in a reference (Zhou et al. 2018). The sample length is 2 cm, and the number of samples is six except case No.5 and NO.18 (5 chips). The duplicate tests were conducted for each test. The sample holder is comprised of plates, and two sides subtracting frames. The distance between the two sample holders is 70 mm. The sample holder could support the maximum span of 50 cm. During the test, the wood chip is installed on two frames by exposing 7 cm to fire. The balance is used to obtain the mass loss varying test time. It has a 0.001 g resolution and 20 Hz frequency. The camera is employed to capture the flame spread profile. During our test, the bottom wood chip is ignited for 3 s firstly. Regarding case No.1, No.7, No.12, No.18, the ignition time lasted for 5 s because of thickness = 7 mm. 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. All tests are performed under a hood without ventilation. Ambient temperature and moisture are 19–24°C and 15–36%, respectively.

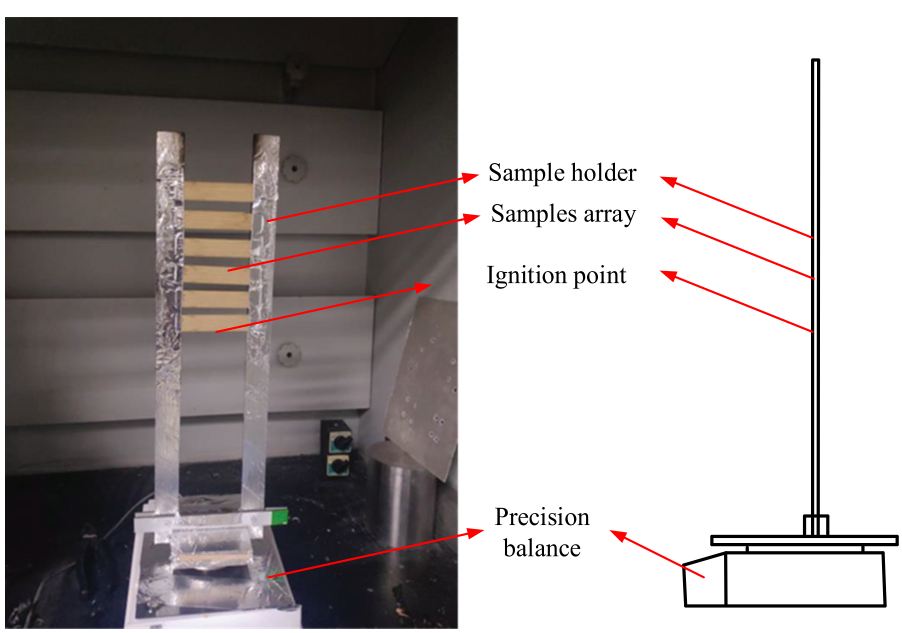



Figure 1. Experimental apparatus description. Left: front-view image. Right: side-view schematics.

**Table 1.** The description of flame spread test over discrete weathered or traditional wood chips.

| Test No. | Weathering or not | Woodgrain | Sample thickness (mm) | Gap size (cm) | Average total burning duration (s) | Average MLR (g/s) | Peak MLR (g/s) | Flame spread rate (mm/s) | Flame length (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | YES | Horizontal | 7 | 1 | 155 | 0.064 | 0.120 | 1.00 | 303 |
| 2 | YES | Horizontal | 5 | 1 | 76 | 0.063 | 0.158 | 2.05 | 350 |
| 3 | YES | Horizontal | 3 | 1 | 69 | 0.089 | 0.242 | 3.20 | 375 |
| 4 | YES | Horizontal | 3 | 2 | 83 | 0.083 | 0.216 | 3.38 | 370 |
| 5 | YES | Horizontal | 1 | 1 | 30 | 0.097 | 0.248 | 11.98 | 449 |
| 6 | YES | Horizontal | 1 | 2 | 22 | 0.114 | 0.259 | 20.40 | 532 |
| 7 | NO | Horizontal | 7 | 1 | 152 | 0.089 | 0.161 | 1.17 | 347 |
| 8 | NO | Horizontal | 5 | 1 | 91 | 0.088 | 0.200 | 2.10 | 361 |
| 9 | NO | Horizontal | 3 | 1 | 68 | 0.114 | 0.230 | 3.21 | 370 |
| 10 | NO | Horizontal | 3 | 2 | 68 | 0.118 | 0.243 | 5.30 | 400 |
| 11 | NO | Horizontal | 1 | 1 | 34 | 0.092 | 0.253 | 11.97 | 445 |
| 12 | NO | Horizontal | 1 | 2 | 20 | 0.168 | 0.303 | 17.78 | 497 |
| 13 | YES | Vertical | 7 | 1 | 263 | 0.054 | 0.136 | 0.63 | 370 |
| 14 | YES | Vertical | 5 | 1 | 160 | 0.077 | 0.200 | 1.72 | 402 |
| 15 | YES | Vertical | 3 | 1 | 89 | 0.091 | 0.182 | 2.14 | 417 |
| 16 | YES | Vertical | 1 | 1 | 39 | 0.066 | 0.239 | 12.86 | 443 |
| 17 | YES | Vertical | 1 | 2 | 17 | 0.135 | 0.209 | 17.83 | 455 |
| 18 | NO | Vertical | 7 | 1 | 177 | 0.069 | 0.137 | 0.96 | 340 |
| 19 | NO | Vertical | 5 | 1 | 118 | 0.103 | 0.251 | 2.30 | 380 |
| 20 | NO | Vertical | 3 | 1 | 87 | 0.091 | 0.214 | 2.59 | 404 |
| 21 | NO | Vertical | 1 | 1 | 36 | 0.068 | 0.236 | 13.05 | 450 |
| 22 | NO | Vertical | 1 | 2 | 19 | 0.138 | 0.243 | 16.09 | 463 |

The details of the test condition are shown in Table 1. The total sample span is the distance between the base edge of the first fuel segment and the top part of the last fuel segment. The wood chips differ from weathered to traditional ones, woodgrain orientation varies from horizontal to vertical, sample thickness changes from 1 mm to 7 mm, air gap increases from 1 cm to 2 cm. Also described in Table 1 are the total burning duration (s), average MLR (g/s), averaged total burning duration (s), the peak of MLR (g/s), averaged flame spread rate (mm/s), and flame length (mm) for each configuration.

### 2.2. Accelerated weathering test methods

The accelerated weathering tests were carried out by the durability test method, which covered water spray, UV light, heating, and cooling process. The weathering process configuration is illustrated in Figure 2. Each cycle consisted of sprinkling water for 4 hours onto the samples, drying at 60°C for 4 h, UV light at 25°C for 6 h, and cooling at −30°C for 10 h. One cycle was conducted each day, and the whole process lasts for 90 days. The temperature of the water sprinkled onto the samples is about 15 ± 3°C. Water is sprinkled through a spray

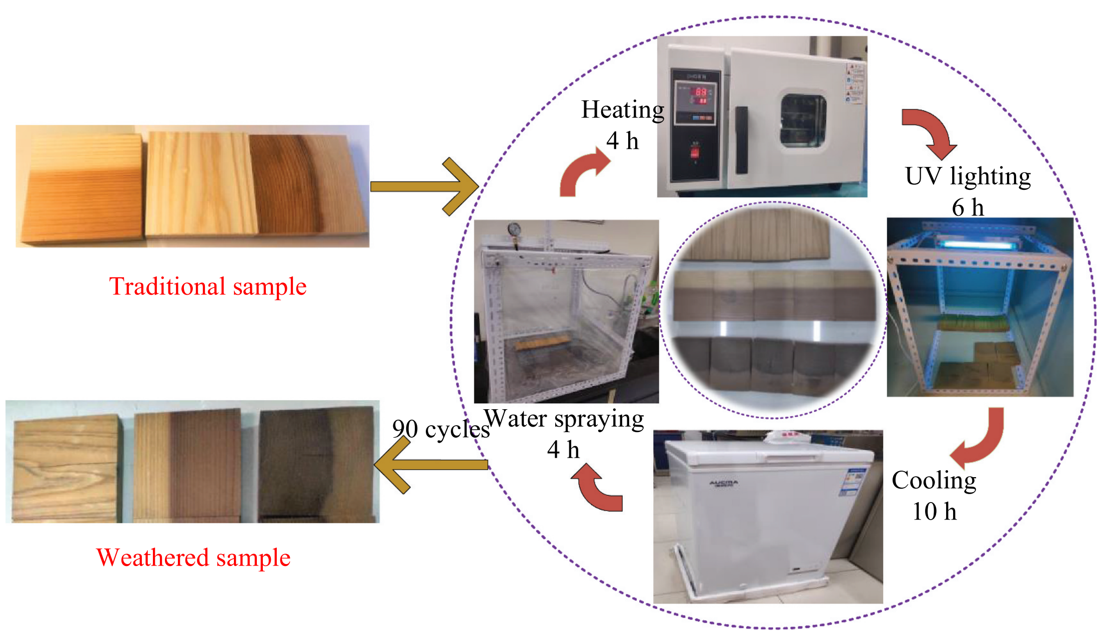



**Figure 2.** The illustration of weathering process configuration.

nozzle that is located above the sample. During the testing, the position of each sample is changed for each different cycle to maintain an averaged sprinkled amount of water of 1 L/($m^2$·min), which is consistent with NT FIRE 053 Method A (Östman and Tsantaridis 2017; Sudol 2014). The UV light is 254 nm. The drying facility has an accuracy of ± 0.3°C. To eliminate the influence of moisture percentage on the flame spread, both traditional and weathered wood chips are treated as nearly 20.0 ± 0.5% by the constant temperature humidity chamber for 96 hours before flame spread tests.

## 3. Results and discussion

### 3.1. The description of averaged MLR and burning duration

The burning durations for all wood chips arelisted in Table 1 and Figure 3. In the current work, the time between the onset of preheating (start time) and ending of total fuel (end time) is defined as burning duration, just as shown in Figure 3(a). In the previous work (Park et al. 2018), the total burning durations were got based on visual confirmation of the recorded video images. To avoid the uncertainty from the observation of flame spread, both the repeated MLR and flame spread profiles are compared to determine the start time and end time. The whole test is described from Figure 3(b,c,d,e,f,g). Regarding test No.5, it is observed during the test that after the bottommost is ignited, the flame spread over the total span within 5 s. Then the length of the flame approached the maximum of 449 mm, which is listed in Table 1. The supply of pyrolysis gas is reduced because of the burn-out located in the base-fuel. The flame length was shortened within 3 s and changed to zero finally. Although the smoldering remained for nearly 50 s, it is ignored presently since it does not contribute to flame spread over discrete fuels.

(a)Mass and MLR versus test time (b) t= 18 s(c) t= 21 s(d) t= 26 s(e) t= 28 s(f) t= 33 s(g) t= 46 s

The description of the averaged total burning duration, MLR, and a peak of MLR is listed in Figure 4 (a,b, c), respectively. It indicates that the artificial weathering process showed a clear effect on the flame spread performance over discrete wood chips. It is a fact that the fire performance of wood has quite different thermal degradation characteristics on the percentage of cellulose, hemicellulose, and lignin (Janssens 2004). The thermal degradation characteristics of wood are found to be shifted toward higher temperatures with increasing lignin content. The reduction of the lignin and hemicellulose component of wood samples due to weathering is found by the results of FTIR results and XRD analysis (Lionetto et al. 2012). Regarding the traditional wood chips, the difference of total burning duration time is small from the comparison of horizontal or vertical grain orientation. In the case of wood with a horizontal grain, it means the flame spread upward across the grain. Similarly, the flame spreads along with the grain orientation concerning the case, which has a vertical grain. Figure 4(a) shows that the burning duration time of the weathered wood chip was divided into two types comparing with the traditional ones. When the flame spreads along with the grain orientation (vertical grains), the burning duration time is enlarged after the treatment of the artificial weathering process. However, the burning duration time of cases that flame spreads across the gain orientation (horizontal grains) is reduced greatly due to the weathering process. It means flame spreads along and across woodgrain orientation is enlarged and slowed down, respectively. The grain orientation affects the heat conductivity of wood, which results in much different flame spread rates across the grain and along the grain was reported (Zhang et al. 2012). This is in part inferred as being relative to the charring rate of wood since the flame spread is very sensitive to it (Hao, Chow, and Lau 2020). Weathering process impacts a clear effect on the flame spread over discrete wood chips (Bahrani et al. 2018; LeVan and Holmes 1986), which was hard to know in the continuous wood. In heritage buildings of China, the wooden column has a vertical grain and the beam has a horizontal grain orientation (Wang et al. 2015). Therefore, it is believable that flame burning duration over a wooden column and beam was enlarged and shorten because of natural weathering, respectively.

Also, the MLR of weathered wood with horizontal orientation is reduced by about 5.6–39.7%, and vertical orientation is decreased by 4.5–33.7% varying the thickness of samples. This consists of the results of peak MLR. After the accelerated weathering process, the peak of MLR is reduced by 2.0–34.2% regarding the sample with horizontal orientation and decreased by 0.7–25.5% concerning samples with vertical orientation. Thus the combustion over discrete weathered wood chips is showed down since the peak of MLR is relative to the intensity of fire performance. This was verified by previous Cone results (Zhou et al. 2018).

### 3.2. Fire spread rate over discrete samples

Flame spread rate is a key index for fire protection of wooden heritage buildings. The flame spread rate was defined as the base-flame spread over discrete samples. A common method is employed by the utilization of MATLAB. The flame intensity over the k-th fuel segment was defined as (Cui and Liao 2019)

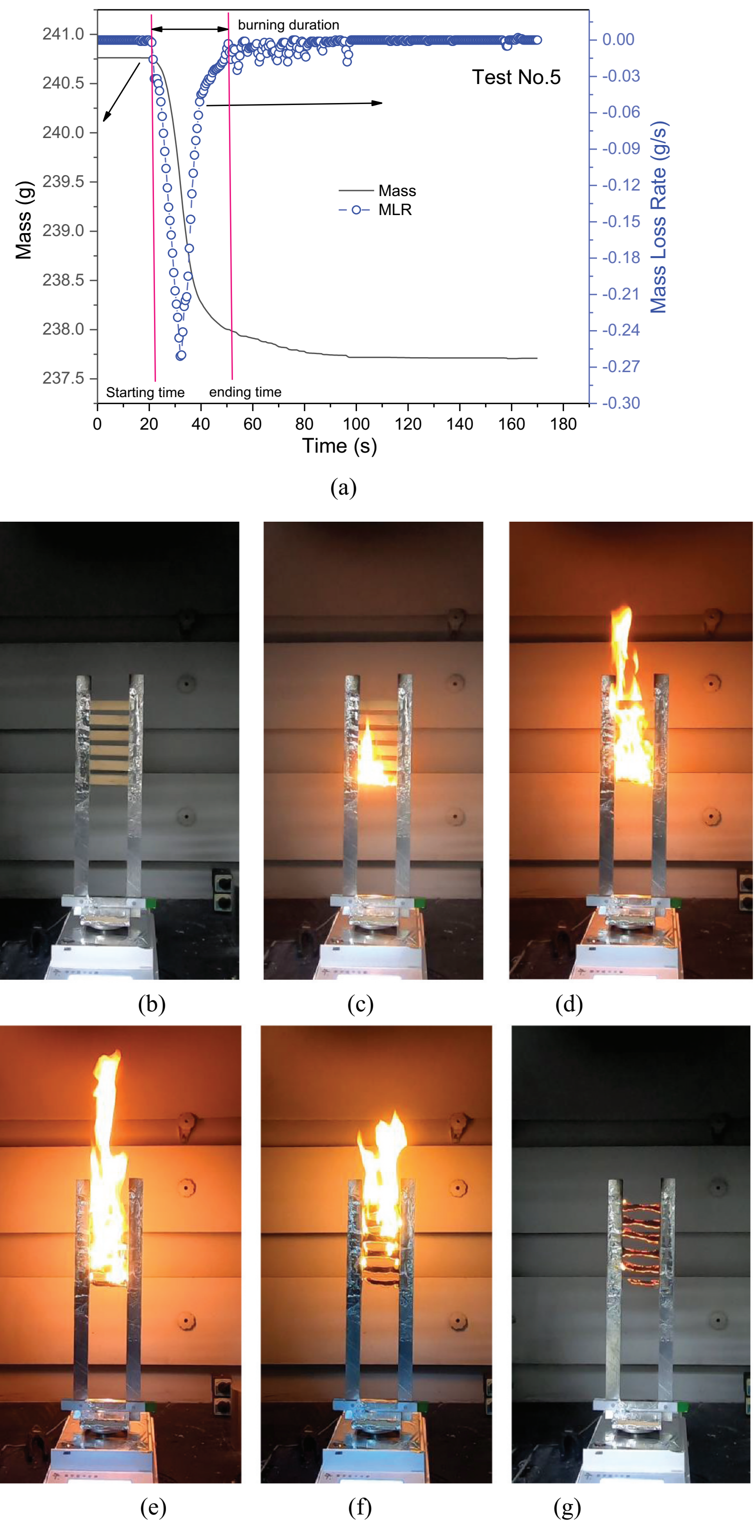



**Figure 3.** The description of MLR varying test time (test No.5) and front-view images of flame spread over discrete fuels with 1 cm gap size at select time instances. (a)Mass and MLR versus test time (b) t= 18 s (c) t = 21 s (d) t = 26 s (e) t = 28 s (f) t = 33 s (g) t = 46 s

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

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.

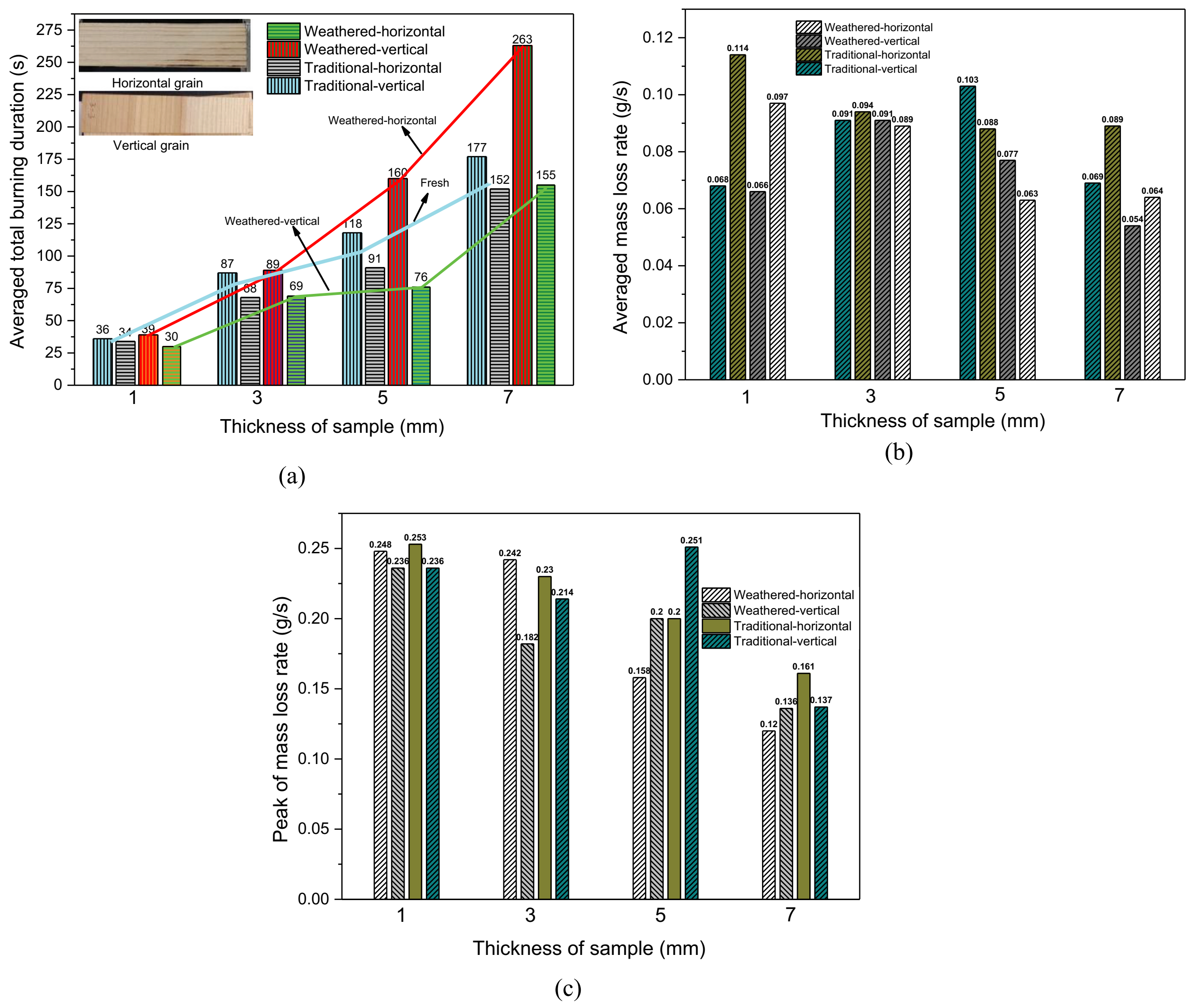
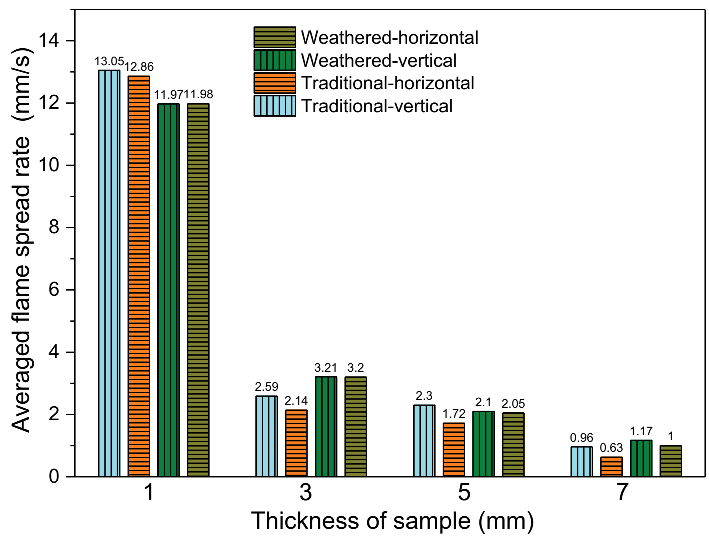



**Figure 4.** The description of the averaged total burning duration, MLR, and peak of MLR. (a) The averaged total burning duration (b) MLR (c) peak of MLR

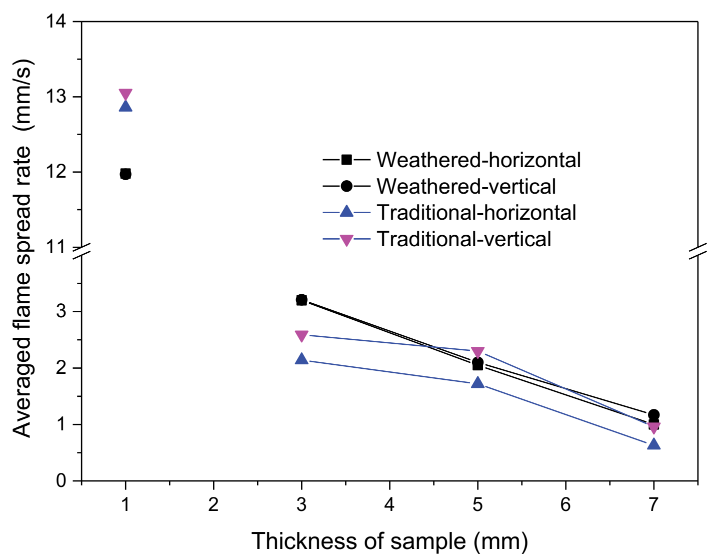
The calculated results are also listed in Table 1. Figure 5 shows the summarization of it. When the thickness of the sample becomes thin, the flame spread rate increases. The flame spread rate was greatly enlarged as the thickness of the sample approaches 1 mm, showed in Figure 5(a). This is relative to the change of thermal-thick to -thin as it becomes thin gradually (Gollner et al. 2012). In general, the thickness differing from 3 mm to 7 mm is linear with averaged flame spread rate. And after the accelerated weathering process, the flame spread is adequately accelerated regarding the sample performed with both vertical and horizontal grain orientation. However, the finding is different regarding the thin samples (1 mm), just as shown in Figure 5(b). The flame spread rate of the sample with a horizontal and vertical grain orientation was reduced by 6.8% and 8.3% due to accelerated weathering, respectively.

### 3.3. Flame length over discrete wood varying samples

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 summarized in Figure 6. The measurement deviations between the repeated tests are also marked by the error bars on Figure 6(a,b,c,d). It was observed that the flame deviation of samples with a vertical grain orientation is generally larger than the ones with horizontal grain orientation. Nearly all the flame length versus thickness of the sample is linear except for one case. Figure 6e summarizes the results of various tests. It suggests that the flame length of the sample which has a horizontal grain orientation (flame across grain orientation), is increased after the weathering process. In contrast, the flame length of samples performed with a vertical grain




(a)




(b)

**Figure 5.** The averaged flame spread rate over discrete samples varying thickness (a) bar (b) line.

orientation (flame along with the grain orientation) is shortened greatly after the weathering process. This is consistent with our previous finding in section 3.1.

### 3.4. Air gaps effects on the averaged burning duration and MLR

In the above discussion, the accelerated weathering process effects on the burning duration, flame spread rate, and MLR have been detailed, respectively. The attempts to clarify air gaps on the burning duration and MLR is conducted in the following content. The flame spread rate for each sample arrangement has been reported by the utilization of the followings equation (Cui and Liao 2019):

$$V_{flame} = \left(L_{gap} + L_{fuel}\right)\left(\frac{d(starttime)}{d(numberoffuel)}\right)^{-1} \quad (1)$$

where $L_{gap}$ and $L_{fuel}$are defined as air gap size and the vertical span of each sample, respectively. For the discrete fuel configuration, the following equation is obtained:

$$V_{flame} = \frac{\dot{q}_f(f)f\delta_f}{\rho dc_p(T_p - T_\infty)} \quad (2)$$

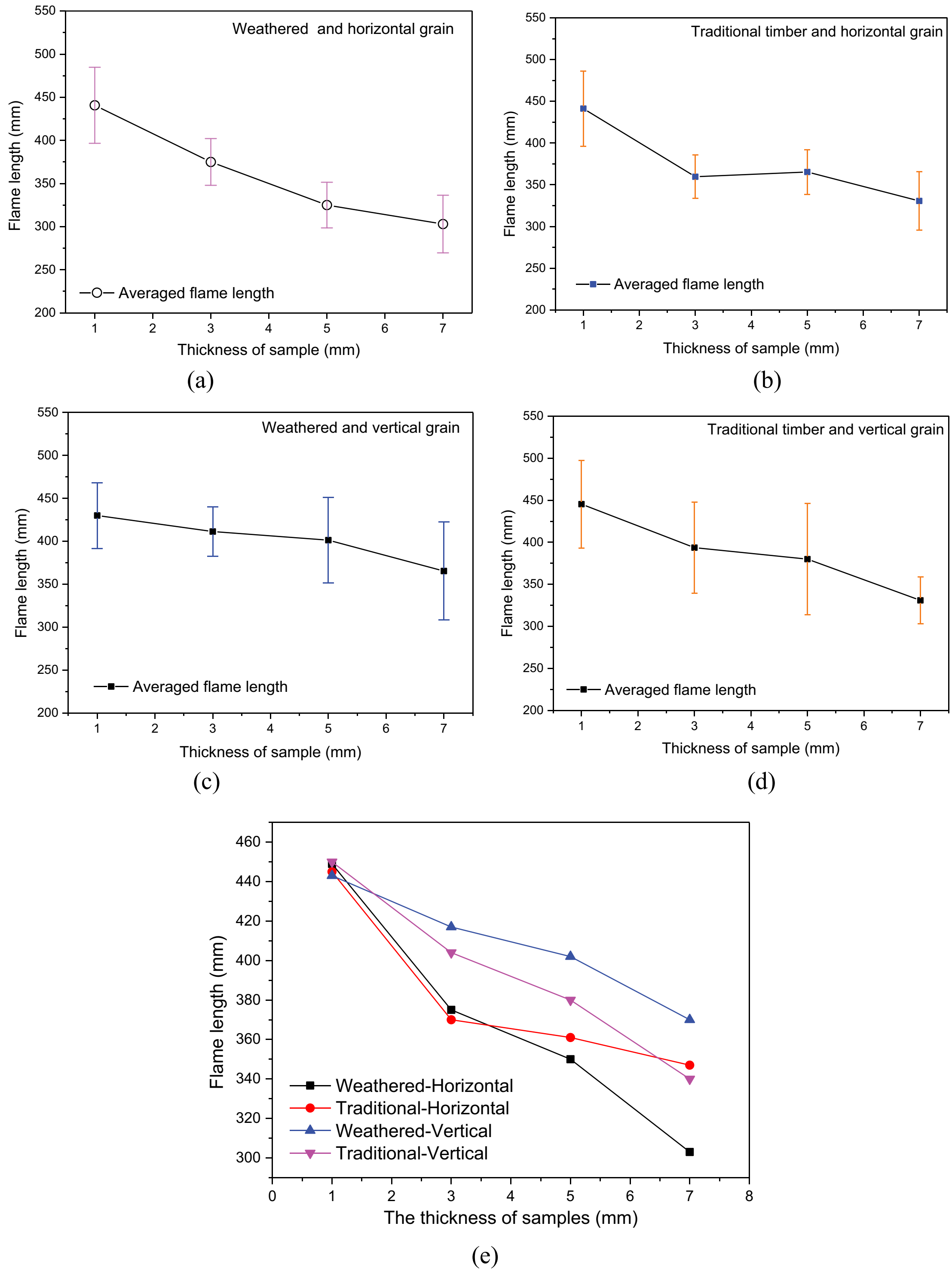
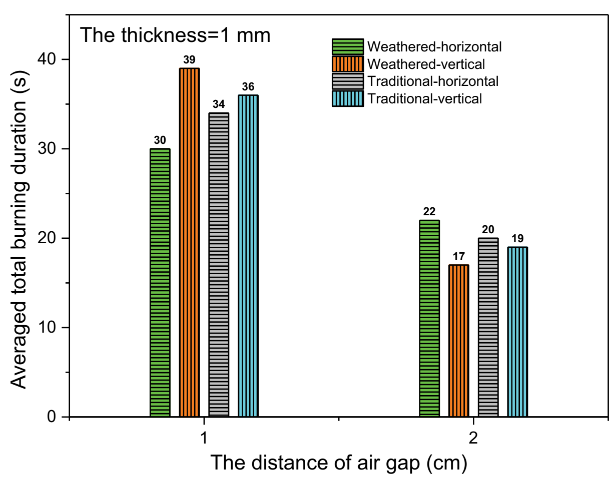



**Figure 6.** The flame length results of different test conditions. (a) weathered-horizontal (b) traditional-horizontal (c) weathered-vertical (d) traditional-vertical (e) flame length varying thickness of sample

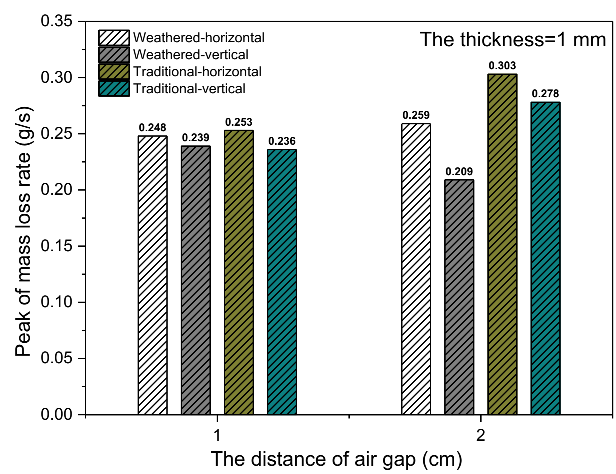
Here $f\rho d$ is defined as apparent area density, $\dot{q}_f''(f)$ indicates the incident heat flux, which is a function of fuel percentage, fuel percentage is $f = \frac{L_{fuel}}{L_{gap}+L_{fuel}}$, and $f\delta_f$ is acted as an effective sample preheat length. Therefore, the flame spread profiles were changed as a variation of the fuel percentage due to air gap size. It is a fact that when the bottommost sample was ignited, the flame-base moves upwards over the sample span and air gap. Air gaps could reduce sample preheating length, flame standoff distance, and sample fuel load, respectively. The dominating effect of the three parts varies from different test conditions. In the current work, when the air gap increases from 1 cm to 2 cm, the total burning duration is generally reduced. The total burning duration of weathered samples with horizontal woodgrain (flame spread across the grain orientation) is reduced by 26.7%, and a vertical grain (flame spread along with the grain orientation) is decreased by 56.4%. Similarly, the total burning duration of traditional samples with horizontal woodgrain (flame spread across the grain orientation) is reduced by 41.1%, and a vertical grain (flame spread along with the grain orientation) is decreased by 47.2%. Regarding the traditional samples, the reduction of burning duration due to the air gap enlargement is similar to horizontal and vertical orientation. In contrast, the decreasing of the burning duration of samples with a vertical orientation is much bigger than the samples with a horizontal orientation. The corresponding results were also found in Figure 7(b), which describes the MLR varying each condition. Although the difference of peak MLR is small among the results of samples performed with a 1 cm air gap, peak MLR of samples performed with traditional wood and 2 cm air gap are much larger than corresponding weathered ones, which is detailed in Figure 7(c). Regarding the flame length of weathered samples (1 mm and horizontal grain orientation), it is increased greatly as the air gap changed from 1 cm to 2 cm. This phenomenon is in part consistent with the previous result that the weathering process shortens the total burning duration but increases the MLR of the sample.

### 3.5. The effects of thickness and air gap on averaged burning duration, MLR, and a peak of MLR

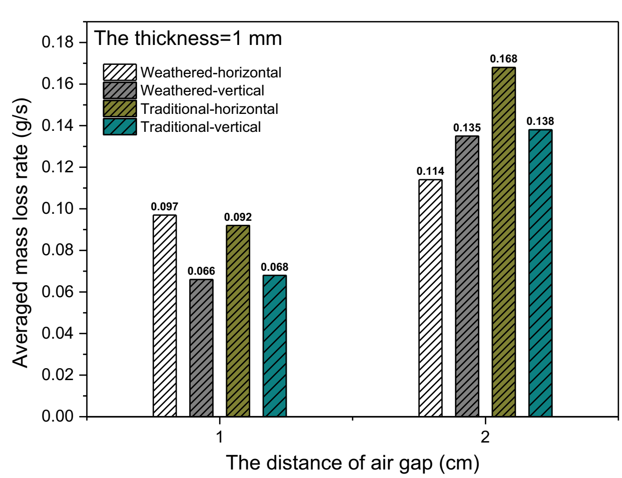
In the above part, the air gap distance influence the burning duration, and MLR was discussed by using




(a)




(b)




(c)

**Figure 7.** The description of the air gap influences the averaged burning duration, MLR, and a peak of MLR. (a) The averaged burning duration (b) MLR (c) peak of ML

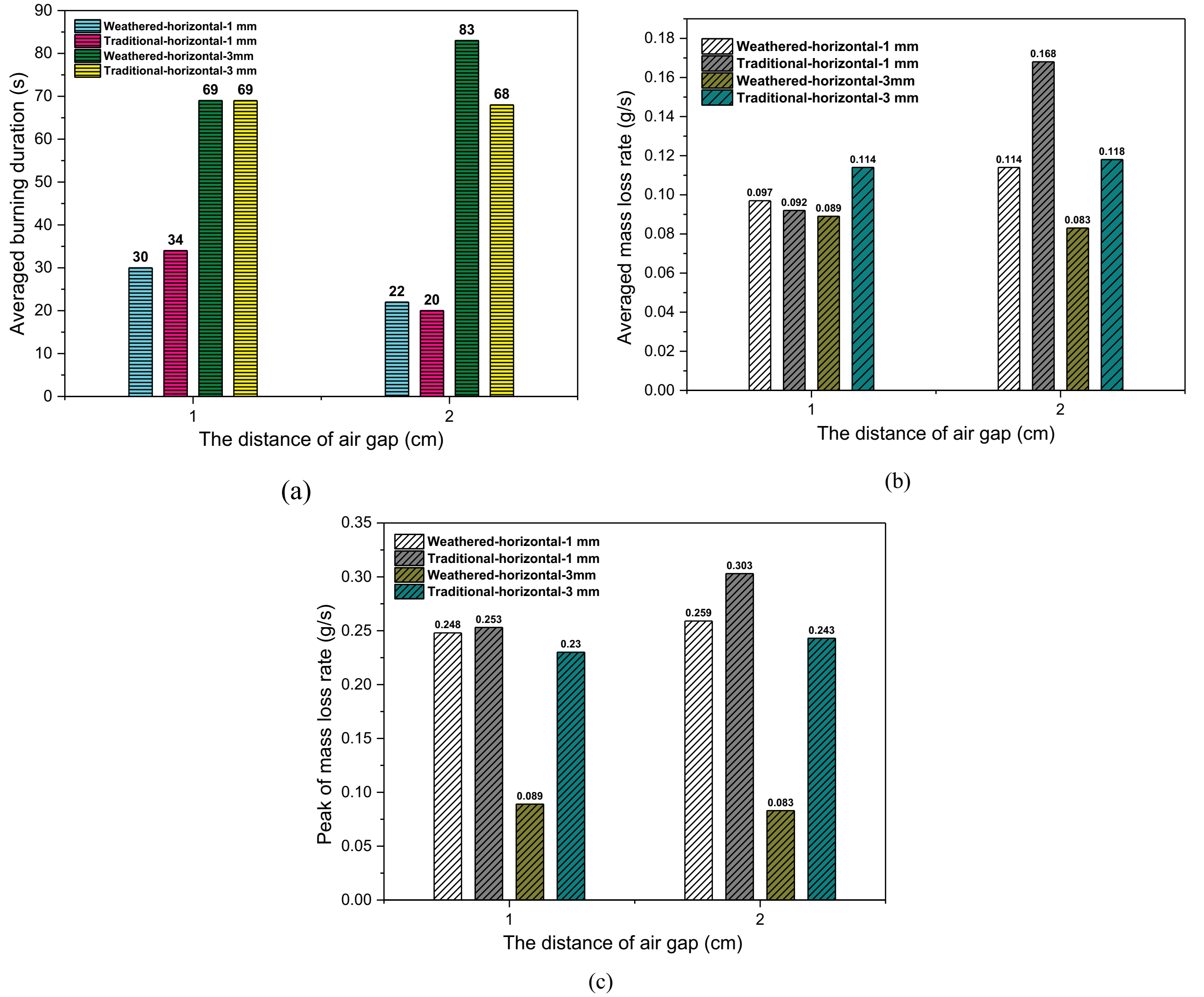



**Figure 8.** The description of the air gap influences the averaged burning duration, MLR, and the peak of MLR. (a) The averaged burning duration (b) MLR (c) peak of ML

cases with a thickness of 1 mm. Here, the effects weathering process impacted on samples is clarified by both 1 mm and 3 mm. The experimental results were shown in Figure 8. To emphasize the influence of thickness and air gap on MLR, only one orientation was used. Regarding the samples with a thickness of 1 mm, the weathering influence was blurred since the values of both burning duration and MLR is similar under two conditions. However, it is worth noting that the burning duration and MLR of the sample with a thickness of 3 mm, are distinguished when the air gap increases from 1 cm to 2 cm. It is inferred to be relative to the leading influence of three factors, the sample preheating length reduction, flame standoff distance, and sample fuel load decreases. These are caused due to the presence of an air gap. Also, MLR and peak MLR of samples (3 mm) before and after weathering process indicate that the air gaps impacted little effects on these two parameters, just as shown in Figure 8(b,c). Under this condition, sample fuel load decrease has the potential to be an important denoting factor. Therefore, as the thickness of samples and air gap increase, the denoting effects transformation happened. For the thick samples (3 mm), the air gap did the little effect on the MLR and peak MLR. The averaged MLR and peak MLR were reduced by about 5.3% and 29.7%, respectively. This agrees with the results of the flame length listed in Table 1. Concerning thin ones (1 mm), MLR and peak MLR increase as the air gap changes from 1 cm to 2 cm.

## 4. Conclusion

In this work, with an aim to discuss the weathering process effects on the flame spread profiles over discrete wooden chips, a series of tests were conducted with the samples before or after the accelerated weathering. The sample differs from horizontal grain orientation to vertical grain orientation, air gaps change from 1 cm to 2 cm, the thickness of samples varies from 1 mm to 7 mm, and the total sample span covers 11 cm to 16 cm. The followings were obtained on the basis of experimental results and detailed analysis:

(1) It shows from experimental results that the accelerated weathering process impacts an important role in the flame spread performance over discrete wood chips. After weathering process, the burning duration of samples was divided into two types comparing with the traditional ones. When the flame spreads along with the grain orientation (vertical woodgrains orientation), the burning duration is enlarged after the treatment of the artificial weathering process. In contrast, the burning duration of cases that flame spreads across the gain orientation (horizontal woodgrains orientation) is reduced greatly due to the weathering. Therefore, it indicates that flame duration time over the wooden column is accelerated and over beam is shortened due to the natural weathering process.
(2) Regarding the flame spread rate, the flame spread is adequately accelerated in engineer after an accelerated weathering process with both vertical and horizontal grain orientation. When the thickness of the sample approaches 1 mm, the flame spread rate was greatly increased. Concerning thick samples (≥3 mm), flame spread rate versus thickness is nearly linear.
(3) Concerning flame length, it suggests that the flame length of samples with a horizontal grain orientation (flame across grain orientation) is increased, and samples performed with a vertical grain orientation (flame along with the grain orientation) are shorten greatly due to accelerated weathering.
(4) Air gaps could impact the flame spread performance by the utilization of three factors, preheating length reduction, flame standoff distance, and sample fuel load decreasing, respectively. The dominating effect varies from different test conditions.
(5) For the thick samples (3 mm), the air gap did little effects on the MLR and peak MLR since sample fuel load decreasing is the potential to be an important denoting factor under this condition.

However, the critical air gap distance for each denoting effect should be further studied.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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## References

An, Z. Y., and Y. Y. Wang (2016) Proceedings of the 2016 International Conference on Education, Management, Computer and Society. S. Yingying, C. Guiran, and L. Zhen (eds), pp. 1947–49.

Bahrani, B., V. Hemmati, A. Zhou, and S. L. Quarles. 2018. Effects of natural weathering on the fire properties of intumescent fire-retardant coatings. *Fire and Materials* 42 (4):413–23. doi:10.1002/fam.2506.

Cui, W., and Y.-T.-T. Liao. 2019. Experimental study of upward flame spread over discrete thin fuels. *Fire Safety Journal* 110:102907. doi:10.1016/j.firesaf.2019.102907.

de Sa, D. M., M. R. Sa, and N. T. Lima. 2018. The National Museum and its role in the history of science and health in Brazil. *Cadernos De Saude Publica* 34 (12): 28–37.

Gollner, M. J., Y. Xie, M. Lee, Y. Nakamura, and A. S. Rangwala. 2012. Burning behavior of vertical matchstick arrays. *Combustion Science and Technology* 184 (5):585–607. doi:10.1080/00102202.2011.652787.

Hao, H., C. L. Chow, and D. Lau. 2020. Effect of heat flux on combustion of different wood species. *Fuel* 278:118325. doi:10.1016/j.fuel.2020.118325.

Janssens, M. L. 2004. Modeling of the thermal degradation of structural wood members exposed to fire. *Fire and Materials* 28 (2-4):199–207. doi:10.1002/fam.848.

Jiang, L., Z. Zhao, W. Tang, C. Miller, J.-H. Sun, and M. J. Gollner. 2019. Flame spread and burning rates through vertical arrays of wooden dowels. *Proceedings of the Combustion Institute* 37 (3):3767–74. doi:10.1016/j.proci.2018.09.008.

Lai, Y., X. Wang, T. B. O. Rockett, J. R. Willmott, H. Zhou, and Y. Zhang. 2020. The effect of preheating on fire propagation on inclined wood by multi-spectrum and schlieren visualisation. *Fire Safety Journal* 118:103223. doi:10.1016/j.firesaf.2020.103223.

LeVan, S. L., and C. A. Holmes (1986) Effectiveness of fire-retardant treatments for shingles after 10 years of outdoor weathering. *Research paper FPL*, 474): 15 p.: ill.; 28 cm. 474.

Li, J., H. Li, B. Zhou, X. Wang, and H. Zhang. 2018. Investigation and statistical analysis of fire loads of 83 historic buildings in Beijing. *International Journal of Architectural Heritage* 14(3), 471–482.

Lionetto, F., R. Del Sole, D. Cannoletta, G. Vasapollo, and A. Maffezzoli. 2012. Monitoring wood degradation during weathering by cellulose crystallinity. *Materials* 5 (10):1910–22. doi:10.3390/ma5101910.

Mackie, P., and F. Sim. 2019. Notre Dame of Paris. *Public Health* 170:A1–A2. doi:10.1016/j.puhe.2019.04.009.

Meng, Q.-X., G.-Q. Zhu, M.-M. Yu, and R.-L. Pan. 2018. The effect of thickness on plywood vertical fire spread. *Procedia Engineering* 211:555–64. doi:10.1016/j.proeng.2017.12.048.

Östman, B.-L., and L. J. I. W. P. J. Tsantaridis. 2017. Durability of the reaction to fire performance of fire-retardant-treated wood products in exterior applications–a 10-year report. 8 (2):94–100.

Östman, B. A. 2017. Fire performance of wood products and timber structures. *International Wood Products Journal* 8 (2):74–79. doi:10.1080/20426445.2017.1320851.

Park, J., J. Brucker, R. Seballos, B. Kwon, and Y.-T.-T. Liao. 2018. Concurrent flame spread over discrete thin fuels. *Combustion and Flame* 191:116–25. doi:10.1016/j.combustflame.2018.01.008.

Popescu, C.-M., and A. Pfriem. 2020. Treatments and modification to improve the reaction to fire of wood and wood based products—An overview. *Fire and Materials* 44 (1):100–11. doi:10.1002/fam.2779.

Rawlinson, K., and D. Gayle (2017) Exeterblazedestroyshotelsaid to be oldest in England. [online] *The Guardian*, Accessed December 30, 2017. https://www.theguardian.com/uk-news/2016/oct/28/exeter fire-threatens-royal-clarence-hotel .

Ren, N., J. de Vries, X. Zhou, M. Chaos, K. V. Meredith, and Y. Wang. 2017. Large-scale fire suppression modeling of corrugated cardboard boxes on wood pallets in rack-storage configurations. *Fire Safety Journal* 91:695–704. doi:10.1016/j.firesaf.2017.04.008.

Song, K., I. Ganguly, I. Eastin, and A. Dichiara. 2020. High temperature and fire behavior of hydrothermally modified wood impregnated with carbon nanomaterials. *Journal of Hazardous Materials* 384:121283. doi:10.1016/j.jhazmat.2019.121283.

Sudol, E. 2014. Weathering resistance of fire-retardant coatings on facade claddings made of selected exotic wood species. Part 1: Review of exposure methods. *Annals of Warsaw University of Life Sciences-SGGW. Forestry and Wood Technology* 86:256.

Turner, C. (2017) Thousands of historic buildings across the country are vulnerable to fire, say experts. [online] Telegraph.co.uk. Accessed December 30, 2017. http://www.telegraph.co.uk/news/uknews/12060749/Thousands-of-historic-buildingsacross-the-country-are-vulnerable-to-fire-say-experts.html .

Wang, M., X. Song, X. Gu, Y. Zhang, and L. Luo. 2015. Rotational behavior of bolted beam-to-column connections with locally cross-laminated glulam. *Journal of Structural Engineering* 141 (4):04014121. doi:10.1061/(ASCE)ST.1943-541X.0001035.

Wang, Q., H. Xiao, W. Wan, Z. Cui, H. Zhu, and J. Sun. 2018. Flame spread on inclined wood surfaces: Influence of external heat flux and ambient oxygen concentration. *Combustion Science and Technology* 190 (1):97–113. doi:10.1080/00102202.2017.1376665.

Wu, J. Q., J. Zhang, and X. H. Zeng. 2017. Research on the status and strategy on fire safety of our country's ancient buildings in the new era(in Chinese). *Water & Wastewater Engineering* 53 (4):85–90.

Yin, W., and H. Yamamoto. 2013. Standing tree assessment for the maintenance of historic wooden buildings: A case study of a World Heritage site in China. *Iforest-Biogeosciences and Forestry* 6:169–74. doi:10.3832/ifor0753-006.

Zeinali, D., A. Gupta, G. Maragkos, G. Agarwal, T. Beji, M. Chaos, Y. Wang, J. Degroote, and B. Merci. 2019. Study of the importance of non-uniform mass density in numerical simulations of fire spread over MDF panels in a corner configuration. *Combustion and Flame* 200:303–15. doi:10.1016/j.combustflame.2018.11.020.

Zhang, Y., J. Ji, J. Li, J. Sun, Q. Wang, and X. Huang. 2012. Effects of altitude and sample width on the characteristics of horizontal flame spread over wood sheets. *Fire Safety Journal* 51:120–25. doi:10.1016/j.firesaf.2012.02.006.

Zhou, B., H. Yoshioka, T. Noguchi, X. Wang, and C. C. Lam. 2018. Experimental study on fire performance of weathered cedar. *International Journal of Architectural Heritage* 13 (8):1195–1208. DOI: 10.1080/15583058.2018.1501115

Zhou, B., X. M. Zhou, and M. Y. Chao. 2012. Fire protection of historic buildings: A case study of Group-living yard in Tianjin. *Journal of Cultural Heritage* 13 (4):389–96. doi:10.1016/j.culher.2011.12.007.

Zhou, X. M., B. Zhou, and J. Xiang. 2010a. Study of fire-extinguishing performance of portable water-mist fire extinguisher in historical buildings. *Journal of Cultural Heritage* 11:392–97. doi:10.1016/j.culher.2010.03.003.

Zhou, X. M., B. A. Zhou, and X. A. Jin. 2010b. Study of fire-extinguishing performance of portable water-mist fire extinguisher in historical buildings. *Journal of Cultural Heritage* 11 (4):392–97.