WOOD RESEARCH **doi.org/10.37763/wr.1336-4561/71.3.467481**
e-ISSN 2729-8906
71(3): 2026 467-481 pp.

INFLUENCE OF TRADITIONAL PLASTER LAYER ON THE COMBUSTION PERFORMANCE OF LARCH AND KOREAN PINE WOOD

YUXIN GUO[1], ZIDONG GUO[1,2], HAILING YUE[1], TIANWEI ZHANG[1]
[1]CHINA PEOPLE'S POLICE UNIVERSITY, CHINA
[2]HEBEI PROVINCIAL KEY LABORATORY OF FIRE PREVENTION AND CONTROL TECHNOLOGY, CHINA

(RECEIVED JUNE 2026)

ABSTRACT

This study investigated the effects of traditional plastering on the combustion behavior of timber used in historic structures. Larch and Korean pine specimens treated with the traditional one hemp fibre and five plaster layer technique were tested using a Fire Propagation Apparatus (FPA). The plaster layer shortened the time to ignition and promoted fire propagation during the early combustion stage, while markedly reducing the peak heat release rate and toxic gas production and increasing the char yield of the wood specimens. These findings clarify the dual effect of traditional plastering on timber combustion and provide experimental evidence for assessing the fire performance of traditionally plastered components in historic timber buildings.

KEYWORDS: Timber plastering layer technique, hemp fiber, combustion performance, ignition time, heat release rate, co and co_2 production rates.

INTRODUCTION

Timber is widely used as a structural material in historic buildings, where long-term preservation often requires surface protection against moisture ingress and biological deterioration. Traditional plastering is one such protective technique in Chinese timber construction. A representative application can be found in the Palace Museum, a historic timber complex (Yang 1998), where the “one hemp fiber with five plastering layers” technique has been applied to major timber components, including columns, beams, and corner rafters (Xu 2021). This treatment consists of a hemp-fiber reinforcement layer combined with multiple plaster layers to form a protective covering over the wood surface. Although its conservation function is well established, the addition of such a surface layer may also modify the ignition and subsequent combustion behavior of the underlying wood. Historical records of repeated fire incidents in the Palace Museum further illustrate the persistent fire risk associated with

timber structures (Lin 2017). Therefore, understanding how traditional plastering affects the combustion performance of wood is important for evaluating the fire behavior of traditionally protected timber components.

Wood combustion is a complex process involving heating, pyrolysis, volatile release, ignition, char formation, and flame propagation, and its fire behavior is influenced by material composition, wood species, environmental exposure, and external heating conditions (Mensah et al. 2022). Differences in the relative contents of hemicellulose and lignin can lead to variations in mass loss, heat transfer, and char formation during combustion (Li 2024; Yuan et al. 2022; Gao et al. 2023). For timber exposed to long-term environmental conditions, aging may further modify its chemical structure and micromorphology and thereby alter its combustion characteristics. Previous studies have reported aging-related changes in ignition behavior, heat release, thermal diffusivity, and char formation in wood (Deng et al. 2023; Zhao et al. 2024; Yan et al. 2022). Such changes may also influence the response of wood to subsequent fire-protection treatments. Wu et al. (2025), for example, found that naturally aged wood exhibited a reduced response to a flame-retardant system. Surface modification and flame-retardant treatment have consequently received considerable attention as approaches to improving wood fire performance. Phosphorus–nitrogen synergistic flame-retardant treatment has been reported to reduce peak heat release rate (HRR), total heat release (THR), and smoke production (Li 2024). However, the performance of these treatments may deteriorate during long-term service. Osvaldová et al. (2022) observed a marked reduction in flame-retardant effectiveness after prolonged exposure, while Fontaine et al. (2022) demonstrated that environmental aging adversely affected the fire behavior of flame-retardant wood-based composites. Experimental studies of wood combustion have commonly employed cone calorimetry, simultaneous thermal analysis, and microscopic characterization to investigate ordinary and engineered wood and to evaluate the effects of parameters such as external heat flux and moisture content on ignition and heat release (Huai 2020; Zhu 2022). More recent studies have also examined the influence of aging on the combustion performance of timber materials (Wang et al. 2024; Long et al. 2025). Despite these advances, most existing research has focused on untreated wood, aged wood, or modern flame-retardant treatments. Traditional plastering differs from conventional flame-retardant treatment in its layered structure, material composition, and original protective purpose, yet its influence on wood combustion has received comparatively limited attention. In particular, the combined effects of traditional plastering on ignition, heat release, fire growth, charring, and gaseous products have not been systematically characterized. Studies employing the Fire Propagation Apparatus (FPA) to evaluate these effects are especially limited.

In this study, laboratory-prepared specimens of larch (*Larix gmelinii (Rupr.) Kuzen.*) and Korean pine (*Pinus koraiensis*) were selected as test materials. Both wood species have been documented as load-bearing timbers used in the Palace Museum (Zhang et al. 2024), but the specimens investigated here were prepared for laboratory testing rather than obtained from historic building components. Untreated specimens and specimens treated using the traditional "one hemp fiber with five plastering layers" technique were tested using an FPA under external heat fluxes of 20, 30, and 40 kW/m². The time to ignition, HRR, THR, fire growth index, and CO and CO_2 production rates were measured to systematically compare the ignition, heat-

release, fire-development, and gaseous-emission characteristics of untreated and plastered wood. The objective of this study is to clarify the influence of the traditional plastering layer on wood combustion behavior and to provide experimental evidence for evaluating the fire performance of traditionally plastered timber components in historic buildings.

MATERIAL AND METHODS

Larch and Korean pine, obtained as modern commercial sawn timber, were selected as the test materials. Wood with visible defects, such as decay, discoloration, and knots, was excluded. The wood was machined into specimens of 100 mm × 100 mm × 100 mm. Dimensional deviations were controlled within ±2 mm. Specimens with missing edges, rough surfaces, or uneven dimensions were discarded.

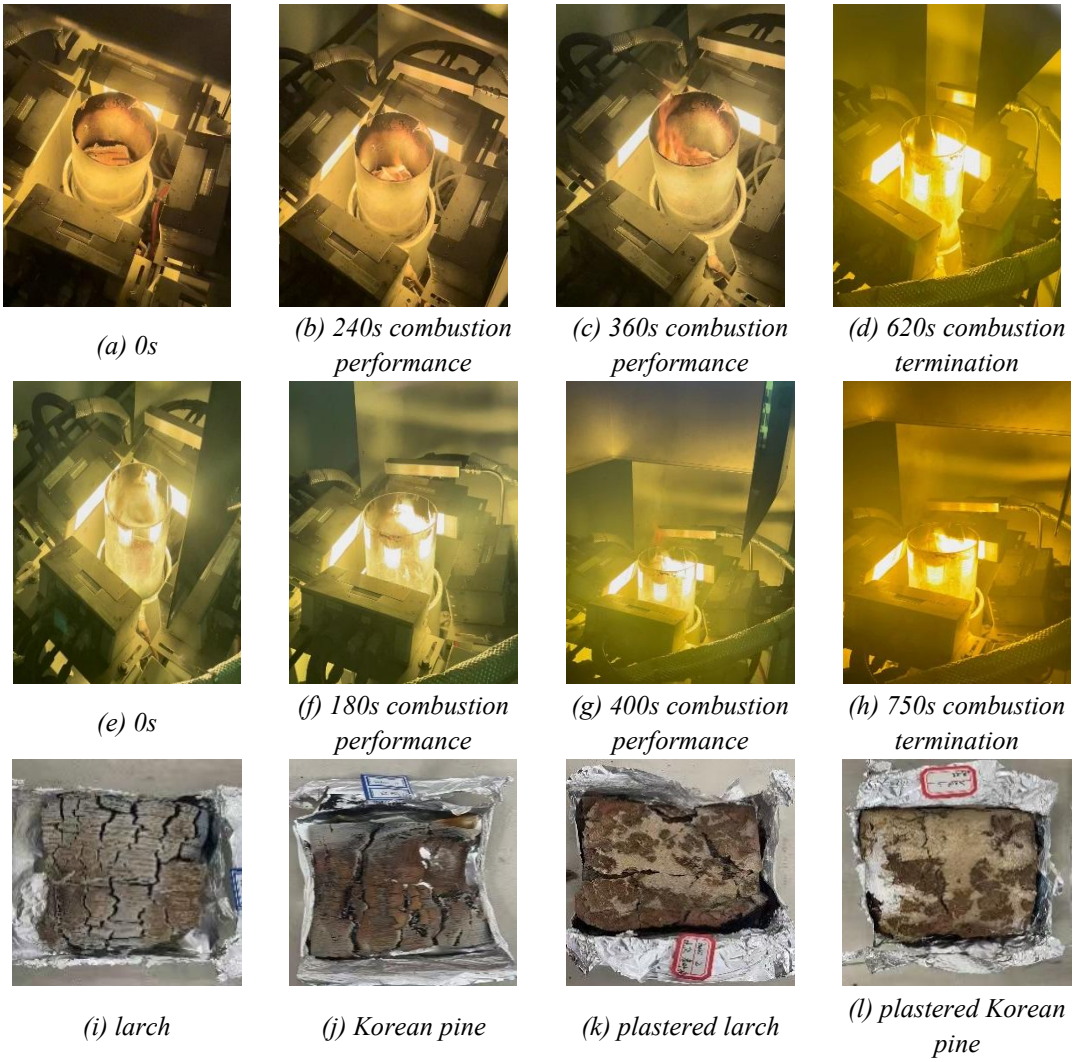
The selected specimens were divided into untreated and plastered groups. The plastered specimens were prepared by an experienced craftsman using the traditional "one hemp layer and five plaster layers" technique. First, gap-filling plaster was applied to fill cracks and surface irregularities. A coarse levelling plaster was then applied to form an even substrate. Next, a hemp-fibre layer was laid on the surface and compacted. Hemp-embedding plaster was subsequently applied over the hemp layer. Intermediate plaster and fine finishing plaster were then applied in sequence. The surface was smoothed during the preparation process. All finished specimens were examined by an experienced craftsman familiar with traditional Chinese ground-layer construction, and the total thickness of the resulting plaster layer was approximately 4 mm. After the final treatment, the specimens were allowed to dry before combustion testing, reaching an equilibrium moisture content of approximately 18%. Four specimen groups were obtained: untreated larch, untreated Korean pine, plastered larch, and plastered Korean pine.

Combustion tests were conducted using a Fire Propagation Apparatus (FPA) in accordance with ISO 12136 (2011) and ASTM E2058 (2019). The FPA continuously measured the concentrations of O_2, CO, and CO_2 during combustion. The weighing system recorded the mass change of each specimen. Heat release rate (HRR) and total heat release (THR) were calculated using the FPA measurement system. The four specimen groups were tested at external heat fluxes of 20, 30, and 40 kW/m². Two replicate tests were conducted under each condition, and the mean values were used for subsequent analysis. A total of 24 combustion tests were performed.

RESULTS AND DISCUSSION

Experimental phenomenon

As illustrated in Fig. 1, the combustion behavior of specimens without the plaster layer is shown in (a)–(d), while that of specimens with the plaster layer is shown in (e)–(h). The plastered wood exhibits a shorter ignition time compared to the untreated wood; however, its total combustion duration is longer. During combustion, substantial black smoke is generated, and the residual char yield of the plastered specimens is higher than that of the untreated ones.



(a) 0s *(b) 240s combustion performance* *(c) 360s combustion performance* *(d) 620s combustion termination*

(e) 0s *(f) 180s combustion performance* *(g) 400s combustion performance* *(h) 750s combustion termination*

(i) larch *(j) Korean pine* *(k) plastered larch* *(l) plastered Korean pine*

Fig. 1: (a)–(d) Combustion behavior of untreated wood; (e)–(h) Combustion behavior of plastered wood; (i)–(l) Char residue of larch, Korean pine, plastered larch, and plastered Korean pine after combustion.

Comparative experimental study on the combustion performance of larch and plastered larch

Tab. 1 shows the combustion performance of larch and plastered larch at different radiant heat fluxes. The following sections will each be discussed separately.

Tab. 1: Combustion performance under varying heat flux intensities.

Wood	Heat radiation intensity (kW/ m^2)	Ignition time (s)	$\frac{1}{\sqrt{t}}$	Heat release rate (kW/m^2)		Total heat release (kW/m^2)	Fire growth index (kW/ (s · m^2))	
				Average value	Peak value		FGI_{fpe}	FGI_{spe}
Larch	20	324	0.0556	217.17	697.64	140.52	1.01	1.19
	30	218	0.0677	184.41	670.87	123.00	1.79	1.47
	40	128	0.0884	172.26	667.46	110.41	2.58	1.59
Plastered	20	200	0.0707	167.27	634.87	148.22	1.35	0.86
larch	30	136	0.0857	171.20	516.51	164.91	2.16	0.89
	40	62	0.1270	204.23	498.23	152.34	3.48	0.93

Ignition time

The ignition time decreases with increasing heat radiation intensity (Tab. 1). The plastered larch exhibits a shortened ignition time, and this effect becomes more pronounced as the heat radiation intensity increases. For instance, under a heat flux of 40 kW/m², the ignition time of plastered larch is 48.4%. Traditional plaster layers contain organic components such as hemp fibres, which may affect the early thermal response and ignition behaviour of the specimens during heating (Zhou et al. 2010). Zhang (2019) employed the Janssens' method to establish a correlation between ignition time and external radiation, proposing a corresponding ignition model. From the data presented in Tab. 1, it can be observed that a power function relationship exists between the reciprocal of the square root of ignition time and the external heat flux.

As shown in Fig. 2, a linear relationship exists between the external heat radiation intensity and the reciprocal of the square root of ignition time. Therefore, by plotting the external heat radiation intensity against the reciprocal of the square root of ignition time, the relationship can be linearly fitted. The fitted equations for the relationship between heat radiation intensity and the reciprocal of the square root of ignition time are presented in Eq. 1 and 2.

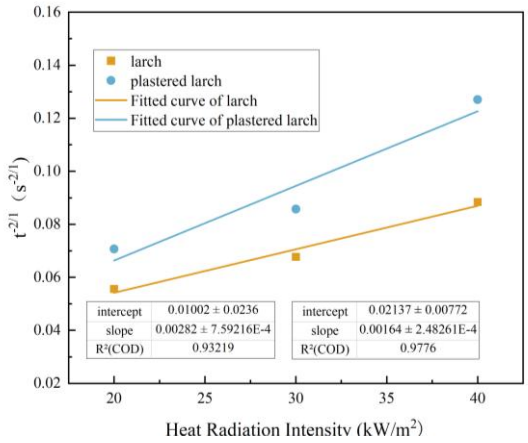


Fig. 2: Relationship between heat radiation intensity and the square root of time to ignition ($TTI^{\frac{1}{2}}$).

Larch
$$TTI^{\frac{1}{2}} = 0.00164q_e^{''} + 0.2137 \quad (1)$$

Plastered larch
$$TTI^{\frac{1}{2}} = 0.00282q_e^{''} + 0.010 \quad (2)$$

Heat release rate

During the experiments, the combustion duration of wood ranged from 300 s to 500 s, with the maximum heat release rate (HRR) ranging from 500 kW/m² to 650 kW/m². For the same material, as the heat radiation intensity increased, the ignition time, the time to reach the peak HRR, and the total combustion duration all decreased. HRR curves of wood exhibit two distinct peaks, a characteristic feature of wood combustion. Liu (2016) suggested that this phenomenon is primarily attributed to differences in the pyrolysis behavior of the chemical components within the wood.

A comparison of HRR of larch and plastered larch, as illustrated in Fig. 3, reveals three key effects of the plaster process on HRR curve of larch. First, the plaster layer shortens the ignition time of larch. Second, the plaster layer prolongs the combustion duration of the

wood, and this effect becomes more pronounced with increasing external heat flux. For example, under a heat flux of 40 kW/m², the combustion duration was extended by approximately 150 s. It can also be observed that under a heat flux of 20 kW/m², the peak of HRR is higher than that under 30 kW/m² and 40 kW/m². This is due to the longer ignition time, which allows more moisture within the wood to evaporate before combustion, resulting in a lower moisture content and the formation of extensive cracks. This increases the combustion area, which is positively correlated with HRR. Third, the plaster layer reduces the peak of HRR. The reduction in the first peak is relatively modest, whereas the reduction in the second peak is more substantial.

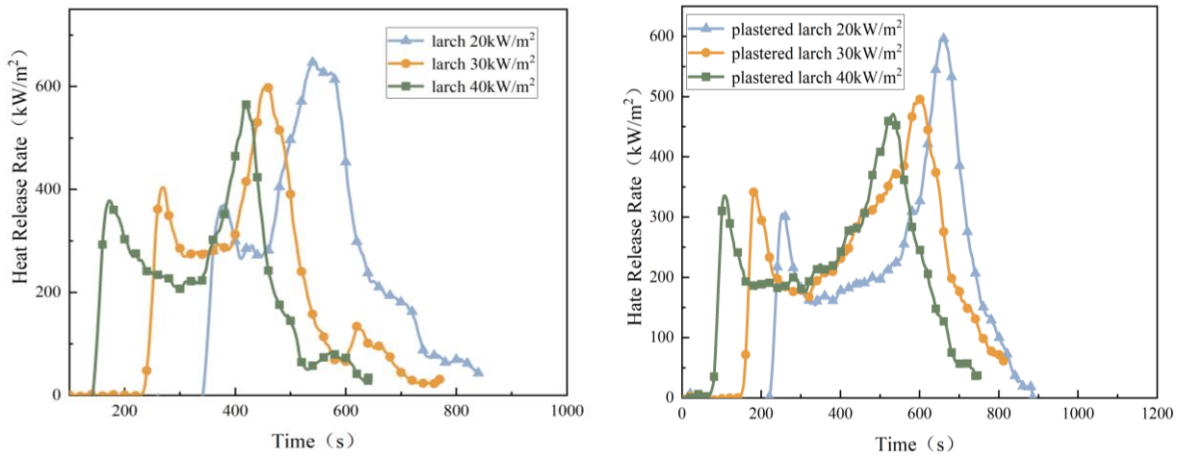


Fig. 3: Heat release rate curves of larch and plastered larch under different heat radiation fluxes. (a) larch, (b) plastered larch.

Total heat release

Fig. 4 presents the variation in total heat release (THR) of larch and plastered larch over time under different heat flux intensities. Under the same external heat flux, THR of plastered larch increases at a slightly lower rate in the early stage compared to untreated larch, while the growth rates converge in the later stage. THR of plastered larch is greater than that of untreated larch. For untreated larch, under external heat fluxes ranging from 20 kW/m² to 40 kW/m², THR exhibits a pronounced negative correlation with heat flux. In contrast, for plastered larch, THR shows relatively little variation across the same range of heat flux intensities.

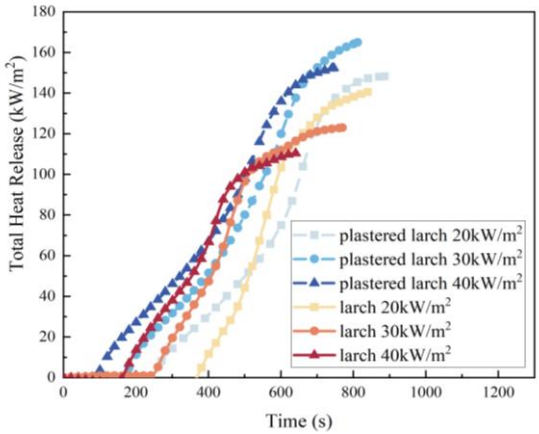


Fig. 4: Relationship between total heat release of larch and plastered larch over time and under different external heat radiation fluxes.

Fire growth index

As shown in Tab. 1, the fire growth index values corresponding to both the first and second peaks of HRR increase with increasing external heat flux. As illustrated in Fig. 5, the fire growth index values for both peaks exhibit a strong linear relationship with the external heat flux. The fitted relationships between the fire growth index and the external heat flux are presented in Tab. 2.

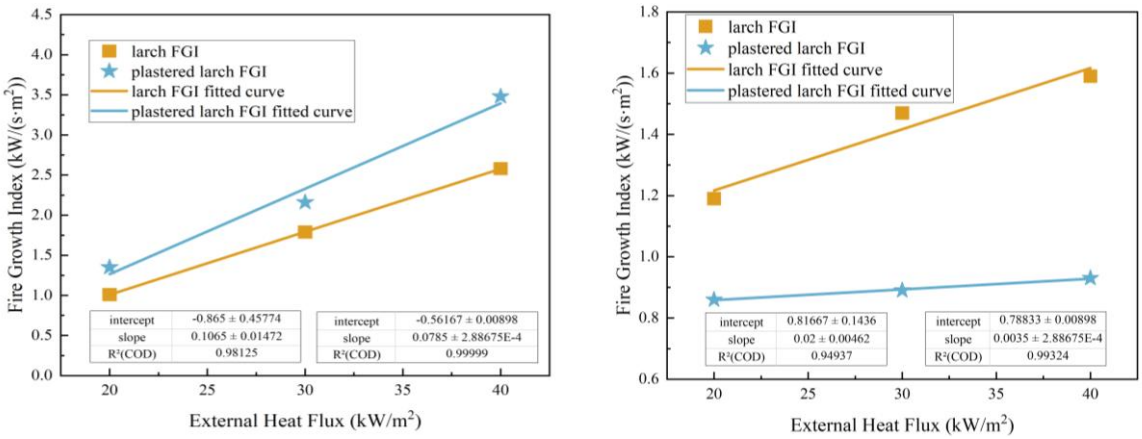


Fig. 5: Relationship between fire growth index of larch and plastered larch and external heat radiation flux. (a) FGI_{fpe}, (b) FGI_{spe}.

Tab. 2: Fitted relationships between fire growth index and external heat flux for larch and plastered larch.

Wood	FGI_{fpe}	FGI_{spe}
Larch	$FGI_{fpe} = 0.0785q_e^{"} - 0.56$	$FGI_{spe} = 0.8168q_e^{"} + 0.02$
Plastered larch	$FGI_{fpe} = 0.1065q_e^{"} - 0.11$	$FGI_{spe} = 0.0035q_e^{"} + 0.79$

The fire growth index of plastered larch exhibits notable changes. Specifically, the fire growth index corresponding to the first HRR peak is higher for plastered larch than for untreated larch, while the opposite is true for the second peak. Collectively, these observations indicate that plastered larch has a higher fire hazard potential, with more intense fire development during the initial stage of a fire.

CO and CO_2 production rates

Fig. 6 present comparative graphs showing the CO_2 and CO production rates over time during the combustion of larch and plastered larch under three external heat flux conditions. It can be observed that the CO_2 production rate decreases with increasing external heat flux. The CO_2 production rate curve for untreated larch exhibits two distinct peaks, and the CO_2 production rate of plastered larch is lower than that of untreated larch. The most significant reduction, a decrease of 38.3%, occurs under a heat flux of 20 kW/m². The CO production rate of plastered larch is close to 0 g/s during the flaming combustion stage, which is attributed to sufficient oxygen availability, allowing complete combustion and the conversion of carbon in the wood to CO_2. In the initial stage of combustion, a small amount of CO is generated from the plastered larch, likely originating from the flammable volatiles released by the plaster layer.

During the extinguishing stage, the CO production rate is relatively high; however, the CO production rate of plastered larch remains lower, indicating that the plaster process significantly influences the CO concentration released during the combustion.

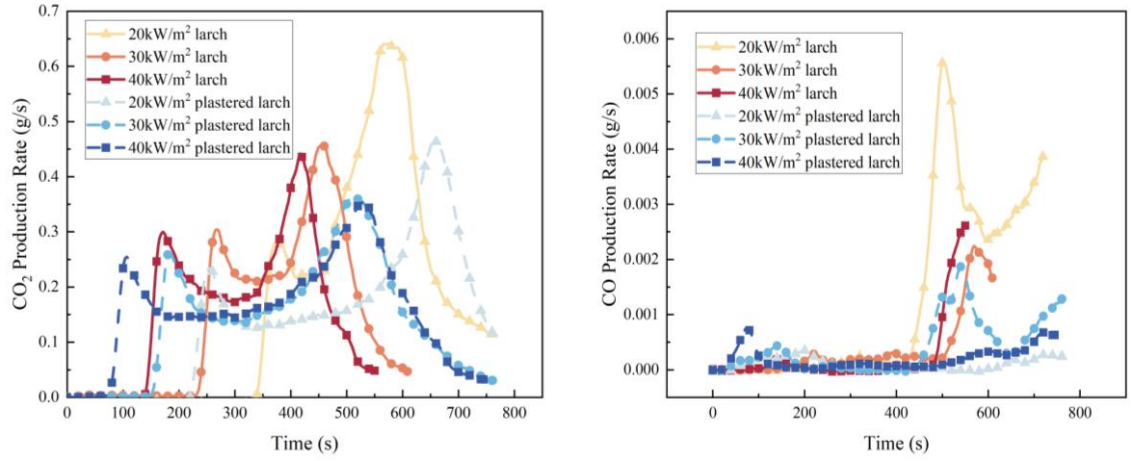


Fig. 6: CO_2 production rate (a) and CO production rate (b) of larch and plastered larch.

Comparative experimental study on the combustion performance of Korean pine and plastered Korean pine

Tab. 3 shows the combustion performance of Korean pine and plastered Korean pine at different radiant heat fluxes. The following sections will each be discussed separately.

Tab. 3: Combustion performance of Korean pine and plastered Korean pine under varying heat flux intensities.

Wood	Heat radiation intensity (kW/m²)	Ignition time (s)	$\frac{1}{\sqrt{t}}$	Heat release rate (kW/m²)		Total heat release (kW/m²)	Fire growth index (kW/(s·m²))	
				Average value	Peak value		FGI_{fpe}	FGI_{spe}
Korean pine	20	331	0.0550	141.27	499.99	101.56	1.21	0.80
	30	204	0.0700	160.48	588.58	88.45	1.79	1.48
	40	83	0.1098	212.12	583.43	94.75	3.81	1.87
plastered	20	210	0.0690	147.8	388.11	128.97	1.47	0.57
Korean	30	122	0.0905	150.67	455.58	116.12	2.72	0.70
Pine	40	56	0.1336	194.21	455.80	124.62	4.42	0.81

Ignition time

As shown in Tab. 3, the variation in ignition time with external heat flux follows the same trend observed for larch, with ignition time decreasing significantly as external heat flux increases. The ignition time of plastered Korean pine is shorter than that of untreated Korean pine, and this effect becomes more pronounced with increasing heat radiation intensity. Fig. 7 presents the relationship between the reciprocal of the square root of ignition time and external heat flux for Korean pine and plastered Korean pine, illustrating a power function relationship.

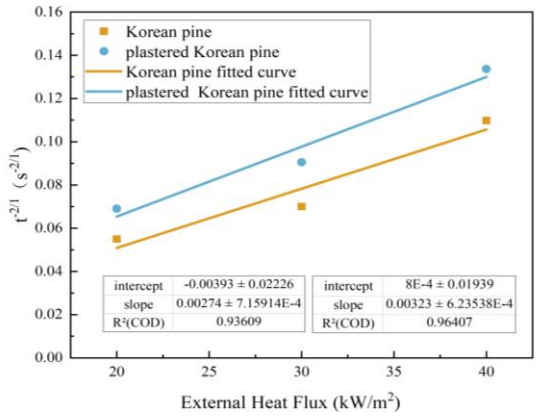


Fig. 7: Relationship between heat radiation intensity and the square root of time to ignition ($TTI^{\frac{1}{2}}$).

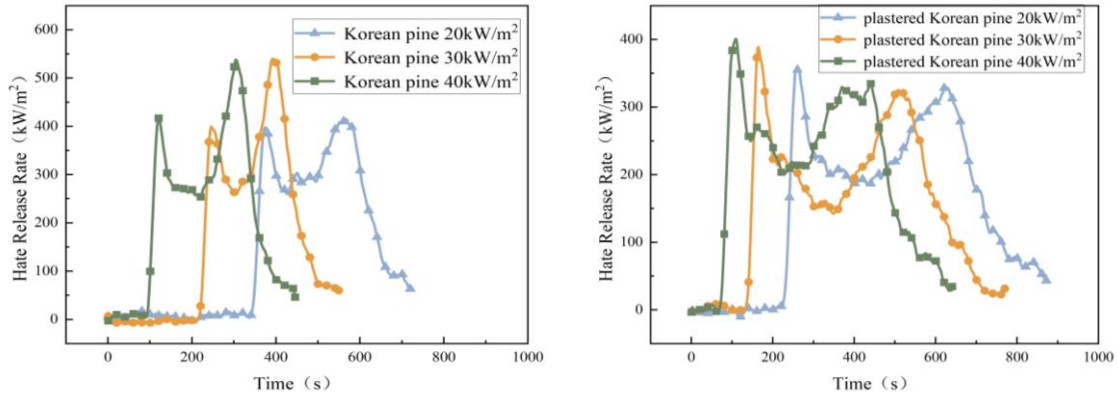
From Fig. 7, a linear correlation is observed between the external heat radiation intensity and the reciprocal of the square root of ignition time. Therefore, linear fitting was performed, and the fitted relationships between heat radiation intensity and the reciprocal of the square root of ignition time are presented in Eqs. 3 and 4.

Korean pine
$$TTI^{\frac{1}{2}} = 0.00274q_e^{''} - 0.00393 \quad (3)$$

Plastered Korean pine
$$TTI^{\frac{1}{2}} = 0.00323q_e^{''} + 0.010 \quad (4)$$

Heat release rate

Fig. 8 presents HRR curves of Korean pine and plastered Korean pine under varying external heat flux conditions. As shown in the figure, the combustion duration of Korean pine ranged from 250 s to 300 s during the experiments, with a maximum HRR of approximately 400–550 kW/m². The combustion duration of plastered Korean pine was approximately 500 s, with a maximum HRR of approximately 350–400 kW/m². The plaster layer limits heat transfer into the wood and reduces the continued release of volatiles during the later stage of combustion. Compared with plastered larch, the later-stage pyrolysis of plastered Korean pine was more strongly suppressed, resulting in a greater reduction in the second heat release rate peak.



a) *b)*

Fig. 8: Heat release rate curves of Korean pine (a) and plastered Korean pine (b) under varying external heat flux.

Total heat release

Fig. 9 presents the variation in THR of Korean pine and plastered Korean pine over time under different heat flux intensities. Combined with the data in Tab. 3, it can be observed that under external heat fluxes ranging from 20 kW/m² to 40 kW/m², THR of both Korean pine and plastered Korean pine at 20 kW/m² was greater than that at 30 kW/m² and 40 kW/m². This is because under lower external heat flux conditions, the wood is subjected to prolonged heating, allowing more moisture to evaporate and cracks to form on the surface, thereby increasing the combustion area, which results in a higher THR compared to that under higher heat flux conditions. As external heat flux increases, THR of the wood gradually increases. Consistent with the observations for larch, THR of plastered Korean pine was higher than that of untreated Korean pine.

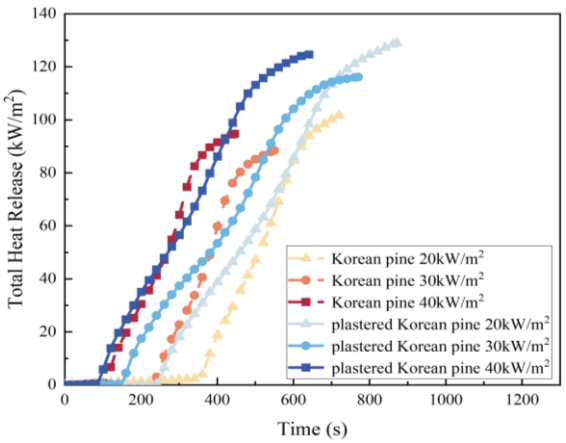
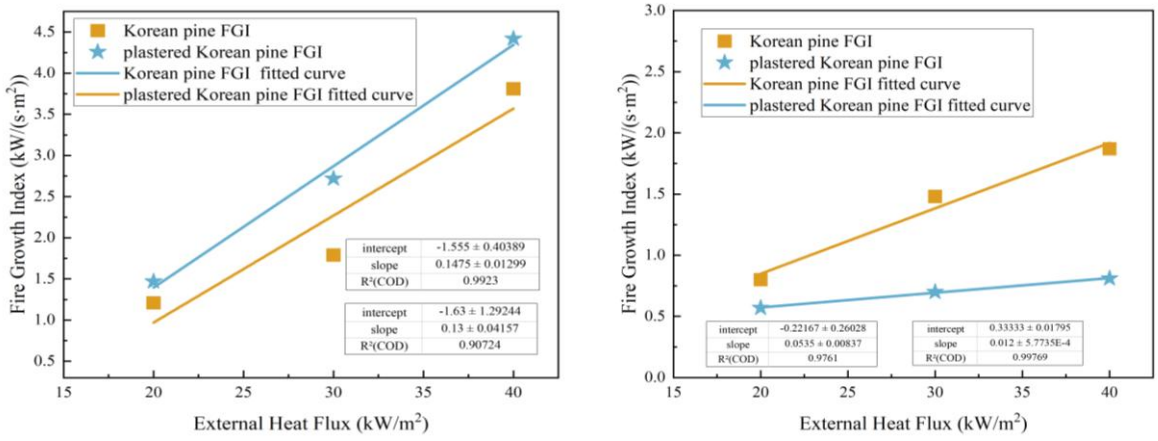


Fig. 9: Variation of total heat release of Korean pine and plastered Korean pine with time and external heat flux.

Fire growth index

Tab. 3 presents the fire growth index values for Korean pine under varying external heat flux intensities. As shown in Tab. 3, the fire growth index values corresponding to both the first and second peaks of HRR increase with increasing external heat flux.



a) *b)*

Fig. 10: Relationship between fire growth index and external heat flux for Korean pine and plastered Korean pine. (a) FGI_{fpe}, (b) FGI_{spe}.

As shown in Fig. 10, the fire growth index values for both the first and second HRR peaks exhibit a strong linear relationship with external heat flux. The fitted relationships between the fire growth index and external heat flux for Korean pine and plastered Korean pine are presented in Tab. 4. The fire growth index of plastered Korean pine exhibits notable changes, similar to those observed for plastered larch. Therefore, in the event of a fire, buildings constructed with plastered Korean pine are expected to experience intense fire development during the initial stage.

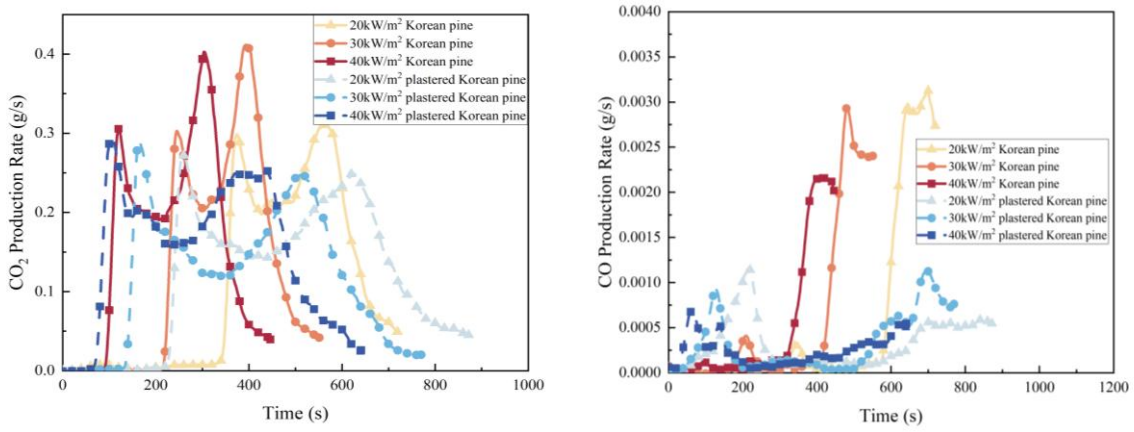
Tab. 4: Fitted relationships between fire growth index and external heat flux.

Wood	FGI_{fpe}	FGI_{spe}
Korean pine	$FGI_{fpe} = 0.13\dot{q}_e^{''} - 1.63$	$FGI_{spe} = 0.0535\dot{q}_e^{''} - 0.22$
Plastered Korean pine	$FGI_{fpe} = 0.1475\dot{q}_e^{''} - 1.55$	$FGI_{spe} = 0.0012\dot{q}_e^{''} + 0.33$

CO and CO_2 production rates

Fig. 11 presents comparative graphs showing the CO_2 and CO production rates over time during the combustion of Korean pine and plastered Korean pine under three external heat flux conditions. It can be observed that the pattern of CO_2 production rate for Korean pine is similar to that of larch. The CO_2 production rate curve for Korean pine exhibits two distinct peaks, and the CO_2 production rate of plastered Korean pine is lower. Unlike larch, the CO_2 production rate of Korean pine increases with increasing external heat flux.

The CO production rate curves for Korean pine and larch share a common characteristic: the CO production rate is significantly reduced after the plaster treatment, indicating that the plastering technique has a notable influence on the CO concentration released during the combustion of Korean pine. A difference between the CO production rate curves of Korean pine and larch is that plastered Korean pine exhibits a distinct peak in CO production rate during the early stage of the experiment. It can be inferred that the CO production rate curve for plastered Korean pine has two peaks: the first peak is attributed to the volatiles released from the plaster layer upon heating, while the second peak results from incomplete combustion during the extinguishing stage.



a) *b)*

Fig. 11: CO_2 production rate (a) and CO production rate (b) of Korean pine and plastered Korean pine.

CONCLUSIONS

Based on the results of small-scale combustion experiments conducted under varying external heat flux intensities, this study systematically elucidates the influence mechanism of the “one hemp fiber and five plastering layers” technique on the combustion performance of typical load-bearing woods used in the Palace Museum. Quantitative comparisons were performed with respect to ignition characteristics, heat release behavior, smoke generation patterns, and char formation. The main findings are as follows: *(1)* The ignition time of wood decreases with increasing external heat radiation intensity. The application of the “one hemp fiber and five plastering layers” treatment significantly shortens the ignition time of wood, and this effect becomes more pronounced at higher heat flux intensities. *(2)* The plastering treatment significantly reduces the peak HRR of wood. For both larch and Korean pine, HRR of plastered specimens are consistently lower than those of untreated specimens. HRR curves exhibit a characteristic double-peak pattern, with the plastering treatment exerting a more pronounced inhibitory effect on the second peak. Furthermore, the treatment alters the trend of HRR under low heat flux conditions, where the peak HRR at 20 kW/m² exceeds that at 30 kW/m² and 40 kW/m², a pattern consistent with that observed for untreated wood. *(3)* Plastered wood exhibits slightly higher THR than untreated wood, but with reduced sensitivity to variations in heat radiation intensity. Regarding the fire growth index, plastered wood shows a higher index corresponding to the first HRR peak compared to untreated wood, while the opposite is observed for the second peak. This indicates that plastered wood experiences more intense fire development in the initial stage, with the fire growth rate slowing in the later stage. *(4)* The plastering treatment significantly reduces the production rates of CO and CO_2 during wood combustion. The most substantial reduction in CO_2 production rate reaches 38.3% (at 20 kW/m²). While untreated wood exhibits a sharp increase in CO production rate during the later stage of combustion, plastered wood maintains consistently low CO production levels throughout the combustion process, effectively reducing the release of toxic and hazardous gases during a fire. *(5)* The char yield of wood decreases with increasing heat radiation intensity for all wood types. Under identical radiation conditions, the char yield of plastered wood is significantly higher than that of untreated wood. This is attributed to the formation of a dense char layer during combustion, which provides thermal insulation and oxygen barrier effects, thereby inhibiting complete combustion and demonstrating a flame-retardant effect.

ACKNOWLEDGMENTS

Supported by Guangdong S&T Programme (2025B0909040002, 2023A1111120002).

REFERENCES

1. YANG, S.Y., 1998: The Palace Museum and fire protection. Zhejiang Fire Protection 1(1): 33.
2. LIN, H., 2017: Fire protection history of the Forbidden City. Talent Resource Development 19(19): 92-94.

3. XU, Q.F., HAN, C.Q., CHEN, L.Z., WANG, Z.C. and LENG, Y.B., 2021: Experimental study on mechanical behavior of timber beams treated with traditional plastering application after exposed to three-side fire. Building Structure 51(9): 92-97+29.
4. MENSAH, R.A., JIANG, L., RENNER, J.S. and XU, Q., 2022: Characterization of the fire behavior of wood: From pyrolysis to fire retardant mechanisms. Journal of Thermal Analysis and Calorimetry 148(4): 1407-1424.
5. LI, Y.H., 2024: Study on wood burning performance under different texture conditions. Fire Science and Technology 43(3): 287-291.
6. YUAN, C.Y., GU, Y.P., LI, M.Q. and CHAI, G.Y., 2022: Combustion characteristics of wood components of ancient buildings under low radiation intensity. Fire Science and Technology 41(8): 1046-1051.
7. GAO, L.Q. and LI, G.Q., 2023: Analysis of temperature elevation characteristics of timber-steel composite members under fire. Building Structure 53(S1): 1964-1969.
8. DENG, J., LIU, T., YAO, M., YI, X., BAI, G.-X., HUANG, Q. and LI, Z., 2023: Comparative study of the combustion and kinetic characteristics of fresh and naturally aged pine wood. Fuel 343: 127962.
9. ZHAO, J., JIANG, X., SONG, J., LU, S., XIAO, Y. and SHU, C.-M., 2024: Influence of natural aging on wood combustion heat release. Wood Science and Technology 58(3): 1227-1257.
10. WU, X.M., LI, H.Y. and WANG, F., 2025: The effect of phytic acid-based flame retardants on the combustion performance and thermal stability of paulownia wood. Journal of Northeast Forestry University 53(3): 125-130.
11. YAN, L., TANG, X.Y., FENG, Y.W., ZHAO, W.J. and XU, Z.S., 2022: Study on combustion characteristics and char formation behavior of compressed densifying flame-retardant wood. Journal of Safety Science and Technology 18(9): 160-166.
12. LI, L.J., 2024: Analysis of thermal stability and combustion performance of high-pressure impregnated flame-retardant wood: A case study of Chinese fir. China Fire Protection (6): 61-64.
13. OSVALDOVÁ, L.M., MITRENGA, P., JANCIK, J., TITKO, M., EFHAMISISI, D. and KOŠUTOVÁ, K., 2022: Fire behavior of treated insulation fiberboards and predictions of its future development based on natural aging simulation. Frontiers in Materials 9: 891167.
14. FONTAINE, G., MARCHETTI, V. and BOURBIGOT, S., 2022: Effects of accelerated and natural weathering on fire-retarded industrial wood composite. Journal of Fire Sciences 40(5): 385-402.
15. HUAI, C.P., 2020: Research on fire spreading characteristics of timber-framed cultural relic building [Master's thesis, Beijing University of Civil Engineering and Architecture].
16. ZHU, C.L., 2022: Analysis and study on combustion performance of artificial wood panel. Construction Quality 40: 18-23.
17. WANG, H.Y., TIAN, Y. and ZHANG, L., 2018: Experimental study of the characteristic parameters of the combustion of the wood of ancient buildings. Journal of Fire Sciences 37(2): 117-136.

18. WANG, K., HAO, D.P., ZHOU, B. and JIANG, C.Y., 2024: Research progress on influence mechanism of aging on wood combustion characteristics. China Safety Science Journal 34(12): 34-39.
19. LONG, M., YI, L., LI, W. and YAN, L., 2025: Fire characteristic evolution and residual bearing capacity analysis of Chinese wooden Dou-Gong brackets under different natural service times. Journal of Thermal Analysis and Calorimetry 150: 14271–14284.
20. ZHANG, Q., CHEN, Y.P. and ZHAO, P., 2024: Overview of wood species used in the timber structures of the Palace Museum - A discussion on the changes of wood materials from the Ming to the Qing Dynasty in the ancient buildings of the Palace Museum. Palace Museum Journal (8): 23-74+156.
21. ISO 12316: Timber structures. Fire resistance of timber members and assemblies.
22. ASTM E2058: Standard test methods for fire tests of roof coverings.
23. BITEAU, H., FUENTES, A., MARLAIR, G., BROHEZ, S. and TORERO, J.L., 2009: Ability of the fire propagation apparatus to characterise the heat release rate of energetic materials. Journal of Hazardous Materials: 916-924.
24. ZHOU, W.H., WANG, L.Q., FAN, X.L., QI, Y., MA, T., 2010: Study on the making techniques and materials of the oil-painting samples from a column in Bogda Khan Palace Museum. Journal of Inner Mongolia University (Natural Science Edition) 41(5): 522–526.
25. ZHANG, X.L., 2019: Thermal decomposition combustion and fire spread characteristics of typical high-speed train interior materials. Doctoral dissertation, University of Science and Technology of China, Pp57-59.
26. LIU, J., 2016: Experimental study of the combustion characteristic of furniture wood with and without combustion improver by cone calorimeter. Master's thesis, University of Science and Technology of China, Pp31-32.

YUXIN GUO
CHINA PEOPLE'S POLICE UNIVERSITY
DEPARTMENT OF FIRE ENGINEERING
NO. 220 XICHANG ROAD, LANGFANG, 065000, CHINA

ZIDONG GUO[1,2*]
[1]CHINA PEOPLE'S POLICE UNIVERSITY
DEPARTMENT OF FIRE ENGINEERING
NO. 220 XICHANG ROAD, LANGFANG, 065000, CHINA
[2]HEBEI PROVINCIAL KEY LABORATORY OF FIRE PREVENTION AND CONTROL TECHNOLOGY
NO. 220 XICHANG ROAD, LANGFANG, 065000, CHINA
*Corresponding author: guozidong@cppu.edu.cn

HAILING YUE
CHINA PEOPLE'S POLICE UNIVERSITY
INVESTIGATION INSTITUTE
NO. 220 XICHANG ROAD, LANGFANG, 065000, CHINA

TIANWEI ZHANG
CHINA PEOPLE'S POLICE UNIVERSITY
COLLEGE OF RESCUE AND COMMAND
NO. 220 XICHANG ROAD, LANGFANG, 065000, CHINA