Characterization of combustion behavior of commercial flame-retardant plywoods in fire propagation apparatus

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Abstract. This paper deals with the combustion behavior and thermal decomposition of two typical kinds of plywoods used in composite floor. The experimental study was performed in fire propagation apparatus and combustion parameters including ignition time, heat release rate, mass loss rate and effective heat of combustion were analysed. The results show that the risk of ignition and heat release of alder is higher than that of Huang Jin Guo Mu under most heat fluxes. Three thermal decomposition stages are proposed according to the characteristics of mass loss rate and temperature profiles. The present work provides input parameters for numerical modeling and gives guidance for fire risk assessment of rail transit.

1. Introduction

As one of the three wood-based panels (plywood, particle board and fiber board), plywood has been widely used as composite floor material in building and train due to its strong rigidity, good vibration damping effect and good sound insulation performance. However, the plywood is flammable even though flame-retarded. The floor structure is located above the transformer and the converter which have potential fire hazards. Once failure occurred it may cause fire and the composite floor will burn and release a lot of toxic smoke, which is a serious threat to people’s lives. Thus, more attention should be drawn to the fire safety of composite floor in train. As the main combustible component of the composite floor, the combustion performance of plywood plays an important role.

Previous researchers have done a lot of work on the ignition, combustion and charring behavior of wood [1-5]. Spearpoint et al. [1] conducted experiments on 50 mm thick samples of wood in cone calorimeter to predict the relationship between ignition time and heat flux, and the result showed that ignition mechanism under heat flux lower than 20 kW m² was different due to char oxidation effect. A modification of plotting ignition time data was proposed by Delichatsios [2] to analyse the thermal intermediate properties of two 4 mm thick plywood s at reduced oxygen atmospheres. Xu et al. [3] used cone calorimeter to investigate the combustion and charring properties of constructional wood species. Batiot et al. [4] explained the thermal degradation of fir wood by analyzing mass loss rate (MLR) and exhaust gases, the process maintained five steps (ignition, carbon layer growth, thermal effect, fuel decrease and smoldering). Similarly, Shi et al. [5] studied the thermal degradation of wood by using MLR and temperature profiles, and three major stages were proposed.
Although much research has been carried out on the analysis of the model estimation of combustion parameters and thermal degradation process for wood, few results are related to the plywood commonly used in rail transit. The combustion behavior of plywood is different from that of wood because it is laminated and is usually flame-retardant. Therefore, it is necessary to study its combustion characteristics. The materials chosen for this study are two typical kinds of plywood widely used in the composite floor of rail transit. Fire propagation apparatus (FPA) is applied in this research to investigate the combustion behavior of plywood when exposed to external heat flux. The ignition property and the energy released are key factors for evaluating the fire risk of materials, thus the combustion behavior of materials is characterized by ignition time ($t_{ig}$), heat release rate (HRR) and effective heat of combustion (EHC) in this study. The thermal degradation stages of the plywood are also determined by the temperature and MLR of materials. The main objectives are to improve the understanding of combustion behavior of plywood for composite floor, and to provide basic data for fire safety.

2. Experiments

2.1. Materials

The commercial flame-retardant plywood used in composite floor of rail transit were provided by CRRC Qingdao Sifang Co., Ltd., including Huang Jin Guo Mu and alder. The Huang Jin Guo Mu is a kind of plywood with good sound insulation performance. In this paper, the abbreviation “HJGM” is used to represent Huang Jin Guo Mu plywood and alder means the alder plywood. The detailed information about the flame retardant and adhesive agent remains confidential and cannot be reported. Preliminary tests were carried out to determine the main properties of plywood and the elementary analysis was compared with the values obtained from literature, as listed in Table 1. Compared with the values obtained in literatures, the concentrations for carbon and oxygen and hydrogen are in the same range, while the nitrogen concentrations are much greater than the untreated woods. This difference could be due to the flame retardants and adhesive used in manufacturing process.

| Category            | HJGM   | Alder  | Fir wood [4] | Plywood [6] |
|---------------------|--------|--------|--------------|-------------|
| Density (kg m$^{-3}$) | 524    | 601    | /            | /           |
| Specific heat (J kg$^{-1}$ K$^{-1}$) | 761    | 942    | /            | /           |
| Thermal conductivity (W m$^{-1}$ K$^{-1}$) | 0.14   | 0.17   | /            | /           |
| Thermal diffusivity (mm$^2$ s$^{-1}$) | 0.36   | 0.30   | /            | /           |
| Heat of combustion (MJ kg$^{-1}$) | 15.51  | 15.80  | /            | /           |
| C element (%)       | 38.5   | 39.2   | 47.4         | 42.6        |
| H element (%)       | 6.7    | 6.7    | 6.18         | 5.5         |
| O element (%)       | 42.3   | 44.1   | 40.7         | 43.9        |
| N element (%)       | 5.7    | 4.8    | <0.1         | 1.9         |

The samples have dimensions of 100 mm×100 mm with a thickness of 5 mm. In order to obtain the moisture content of plywood, the samples were conditioned at 103 °C for 24 h in an oven to remove free water from plywood. The moisture content of plywood samples is 10%±0.7%.

2.2. Apparatus and experimental methods

Combustion tests were conducted under ambient air in an ASTM E 2058 standard FPA made by Fire Testing Technology Limited. The samples were heated by infrared heating system which consisted of four tungsten lamp heaters and a power controller. The heat flux produced by the infrared heating system varied from 0 to 60 kW m$^{-2}$. The load cell ranging from 0-1000 g had an accuracy of 0.1 g. The flow rate of air was set to be 100 L min$^{-1}$. The yield of combustion gases was measured by an oxygen analyzer, a CO and CO$_2$ analyzer, by which the combustion parameters such as HRR and EHC could be calculated. The apparatus was calibrated every day before the experiment.
Combustion tests were carried out with piloted ignition under external heat fluxes of 20–60 kW m$^{-2}$. The ignition pilot was a 10 mm long ethylene/air flame located 10 mm away from the sample surface. In this research, two K type thermocouples with the diameter of 1 mm were mounted in the center of top and bottom surfaces of plywood samples to measure the temperature. The 6 mm thick ceramic paper and 0.030 mm thick aluminum foil were used to make the sample holder. Two layers of aluminum foil wrapped the sample tightly, then three layers of ceramic paper were placed on the bottom of sample, and a single layer was placed around the sides [7]. At last, the sample was wrapped tightly with two layers of aluminum foil. The sample holder could not only effectively prevent heat loss, but also benefit the installation of thermocouples. All experimental conditions were repeated at least three times to ensure the reproducibility of the results.

3. Results and discussions

3.1. Combustion behavior

3.1.1. Ignition time. Ignition time is one of the critical combustion parameters to characterize the fire hazard of materials [8]. $t_{ig}$ was experimentally determined as the interval between the beginning of the test and the existence of a sustained flaming. Sustained flaming defined by ASTM E 2058 means the existence of flame on or over most of the specimen surface for at least a 4 s duration. The average $t_{ig}$ is presented in Table 2 and Figure 1. It can be observed that $t_{ig}$ of the two plywoods is almost the same when heat flux is greater than or equal to 40 kW m$^{-2}$, while the deviation becomes larger with the decrease of heat flux. In general, alder is more likely to be ignited than HJGM.

In agreement with the ASTM E 2058, experimental critical heat flux ($CHF_{exp}$) is the minimum external heat flux required to ignite sample within 900 s. $CHF_{exp}$ is usually regarded as the average value of the lowest heat flux at which ignition is observed and the highest heat flux at which the sample is not ignited within 900 s. Thus, the $CHF_{exp}$ of HJGM and alder are both 22.5 kW m$^{-2}$.

Table 2. Combustion parameters.

| Parameter          | Material | Heat flux (kW m$^{-2}$) | 20 | 25 | 30 | 40 | 50 | 60 |
|--------------------|----------|------------------------|----|----|----|----|----|----|
| $t_{ig}$ (s)       | HJGM     | No ignition            | 522| 232| 109| 63 | 45 |
|                    | Alder    | No ignition            | 287| 176| 92 | 61 | 47 |
| Average $EHC$ (MJ kg$^{-1}$) | HJGM | /                       | 6.6| 5  | 5.9| 6.6| 6.3| 4.5| 4.4| 5.1| 5.1| 5.4|
|                    | Alder    | /                       | 54 | 60 | 81 | 88 | 120|
| Peak $HRR$ (kW m$^{-2}$) | HJGM | /                       | 49 | 80 | 98 | 112| 117|
|                    | Alder    | /                       |    |    |    |    |    |

Figure 1. Relationship between the ignition time and heat flux.
3.1.2. Heat release rate. HRR is an important parameter to assess fire risk of material. Figure 2 shows the HRR of HJGM. As can be seen, the HRR curves have two growth stages with two peaks in each stage when the heat flux is no less than 30 kW m$^{-2}$. While under the lower heat flux (25 kW m$^{-2}$), there are three main peaks occurred. Figure 3 presents the HRR of alder, it shows that there are two growing stages without secondary peaks in the HRR curves when the heat flux is greater than or equal to 30 kW m$^{-2}$. While under the heat flux less than 30 kW m$^{-2}$, there are several secondary peaks occurred in the two main stages. The peak HRR is summarized in Table 2. It shows that the peak HRR of alder is higher than that of HJGM under most heat fluxes.

Compared the HRR curves of these two plywoods, we can find that the first peak occurs immediately after ignition and the stage lasts for a shorter time than the second stage. The reason for the decrease of the first peak HRR is that when the plywood is ignited, a thin layer of char is formed on the surface on account of the addition of flame retardant. The char layer has a low thermal conductivity and thus behaves as a good insulator. The decrease of the first peak HRR for HJGM is smaller than that of alder, indicating that HJGM undergoes a more stable combustion after ignition. With the energy accumulated, the flame grows up again accompanied by the second peak HRR occurred. Compared with the increase of HRR in the first stage, the duration of second stage lasts for a longer time and the peak value is much larger than the first peak because the sample has been fully pyrolyzed.

![Figure 2. The HRR of HJGM under different heat fluxes.](image1)

![Figure 3. The HRR of alder under different heat fluxes.](image2)

3.1.3. Mass loss rate. In order to deepen the understanding of the thermal degradation of plywood, the MLR of the plywoods is analysed. The smoothed MLR is shown in Figure 4. It can be seen from the figure that the trend of MLR curves is similar to that of HRR curves. The MLR increases sharply after ignition and then decreases due to char formation. The time to peak MLR decreases as the heat flux increases while the peak value of MLR increases as the external heat flux increases, indicating that
thermal degradation is more intense under higher heat flux. But the increase in peak MLR is not so obvious when heat flux increases from 40 to 60 kW m\(^{-2}\) due to the blockage effect of char layer, which can be expressed by as follows [9]:

\[
\dot{m} = \frac{\dot{q}^*}{\Delta H^c} = \left[ \dot{q}^*_f (1 - \beta_{ext}) + \dot{q}^*_f (1 - \beta_f) - \sigma (T^*_f - T^*_c) \right] / \Delta H^c
\]

where \(\dot{m}\) is mass loss rate (g s\(^{-1}\) m\(^{-2}\)), \(\Delta H^c\) represents heat of combustion (MJ kg\(^{-1}\)), \(\beta_{ext}\) is radiation heat blockage for external heat flux, \(\dot{q}^*_f\) donates radiative and convective heat flux from flame to sample surface (kW m\(^{-2}\)), \(\beta_f\) is radiative and convective heat blockage of flame radiant heat flux and \(\sigma (T^*_f - T^*_c)\) donates the re-radiation heat loss of sample (kW m\(^{-2}\)). When the external heat flux increases, the radiation blockage also increases, with the result that the increment in peak MLR becomes smaller.

The peak MLR of alder is observed to be higher than that of HJGM, the reason can be explained by the influence of density. The combustion performance of plywood is affected by density, for the specific heat and thermal conductivity depend on the density [10]. The density of alder is higher than that of HJGM, thus the specific heat and thermal conductivity are much larger leading to a higher peak MLR.

3.1.4. Effective heat of combustion. EHC is defined as the average chemical heat of combustion per unit mass of material [11]. It can be determined by the following expression:

\[
EHC = \frac{HRR}{MLR}
\]

EHC donates the actual heat released by material and thus the value depends on the applied external heat flux and time. It can be used to characterize the capability of the material to release heat in reality [12]. The average EHC for HJGM and alder is listed in Table 2. As can be seen, the EHC of alder under different heat fluxes is all slightly smaller than the values for HJGM, which shows that the capability of HJGM to release heat is higher than that of alder. Due to the incomplete combustion, the average EHC measured by FPA under different heat fluxes is far less than the heat of combustion measured by oxygen bomb calorimeter (listed in Table 1).

3.2. Thermal decomposition stages
The temperature and MLR profiles of these two plywoods under external heat flux of 50 kW m\(^{-2}\) are presented in Figure 5. As can be seen, the temperature of top surface rises rapidly once exposed to external heat flux, while the temperature of bottom surface increases slowly. The sudden rise in surface temperature can be regarded as the ignition temperature [13], thus the ignition temperatures of HJGM and alder can be estimated to be 437 °C and 457 °C.
According to the $MLR$ curves shown in Figure 5, the combustion of these samples can be divided into three stages. To explore the combustion temperature range of each stage, the bottom surface temperature is used as the combustion temperature because it represents a change in internal pyrolysis. The combustion temperature ranges of these three stages are 30–109 °C, 109–336 °C and >336 °C for HJGM, and 30–149 °C, 149–300 °C and >300 °C for alder. According to Janssens and Douglas [14], the main components of wood (hemicellulose, cellulose, and lignin) decompose in different temperature ranges. The hemicellulose decomposes in a temperature range of 200~260 °C, cellulose in a range of 240~350 °C, and lignin in a range of 280~500 °C. The char layer is formed on the 300 °C isotherm [15].

![Figure 5. The temperature and MLR profiles under the external heat flux of 50 kW m$^{-2}$.](image)

Based on the above information, we can infer that the first stage of mass loss is caused by the evaporation of water and combustion of sample surface. On the surface of plywood, ignition occurs due to sufficient combustible gases mixed with air and flame spreads to the entire surface, then the flame is smaller or extinguished. The bottom temperature increases gradually and exceeds 100 °C, leading to the volatilization of water.

In the second stage, hemicellulose, cellulose and lignin decompose with the fierce combustion of upper layer of plywood. At the end of the second stage, the bottom temperature increases significantly accompanied by the formation of char layer. The char layer continues to form thermal insulation between the surface and the deep layer of plywood, bringing about a decrease of $MLR$ in the end of the second stage. In this process, pyrolysis gases are blocked by the char layer and cannot be diffused upward, and then the pressure increases on the deep layer behind it.

The third stage when temperature is higher than 300 °C may be the decomposition of remaining lignin and char. The pressure behind the char layer is released and the plywood arches to the middle rapidly accompanied by intense burning, resulting in a third major peak of $MLR$. The scorching char layer remains smoldering when the flame goes out.

### 4. Conclusions

The combustion behavior and thermal decomposition of two typical kinds of plywoods used in composite floor of rail transit were studied experimentally in FPA with external heat fluxes from 20 to 60 kW m$^{-2}$. The main results are as follows:

1. The ignition time of the two plywoods is almost the same when heat flux is greater than or equal to 40 kW m$^{-2}$, while the deviation becomes larger with the decrease of heat flux.
2. There are two growing stages in $HRR$ history for these two plywoods and the first peak occurs immediately after ignition and the stage lasts for a shorter time than the second stage due to char formation. The duration of second stage lasts for a longer time and the peak value is much larger than the first peak because the sample is fully pyrolyzed.
3. The densities of alder and HJGM decrease in order, thus the peak $MLR$ of alder is higher than that of HJGM.
(4) The $EHC$ of alder is slightly smaller than that for HJGM under different heat fluxes.

(5) The thermal decomposition of the plywood can be divided into three stages based on the $MLR$ and temperature profile.

The present work is part of the research on the fire dynamics of plywood used in composite floor. It provides input parameters for numerical modeling and gives guidance for fire risk assessment of rail transit.

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References
[1] Spearpoint M J and Quintiere J G 2001 Predicting the piloted ignition of wood in the cone calorimeter using an integral model — effect of species, grain orientation and heat flux *Fire Safety Journal* **36** 391
[2] Delichatsios M A 2005 Piloted ignition times, critical heat fluxes and mass loss rates at reduced oxygen atmospheres *Fire Safety Journal* **40** 197
[3] Xu Q, Chen L, Harries K A, Zhang F, Liu Q and Feng J 2015 Combustion and charring properties of five common constructional wood species from cone calorimeter tests *Construction and Building Materials* **96** 416
[4] Batiot B, Luche J and Rogaume T 2014 Thermal and chemical analysis of flammability and combustibility of fir wood in cone calorimeter coupled to FTIR apparatus *Fire and Materials* **38** 418
[5] Shi L and Chew M Y L 2013 Experimental study of woods under external heat flux by autoignition: Ignition time and mass loss rate *Journal of Thermal Analysis and Calorimetry* **111** 1399
[6] Fateh T, Rogaume T, Luche J, Richard F and Jabouille F 2013 Modeling of the thermal decomposition of a treated plywood from thermo-gravimetry and Fourier-transformed infrared spectroscopy experimental analysis *Journal of Analytical and Applied Pyrolysis* **101** 35
[7] Delichatsios M A 2000 Ignition times for thermally thick and intermediate conditions in flat and cylindrical geometries *Fire Safety Science* **6** 233
[8] Quintiere J G 2006 A theoretical basis for flammability properties *Fire and Materials* **30** 175
[9] Zhang X, Zhao Y, Zhang T, Ding Z, Li C and Lu S 2019 Characterization of thermal decomposition and combustion for commercial flame-retardant rubber floor cloth in TG–FTIR and FPA *Journal of Thermal Analysis and Calorimetry* **135** 3453
[10] Harada T 2001 Time to ignition, heat release rate and fire endurance time of wood in cone calorimeter test *Fire and Materials* **25** 161
[11] ASTM E2058-13a, Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA). ASTM International, West Conshohocken, PA, 2013, DOI: 10.1520/E2058-13
[12] Chen R, Lu S, Li C, Li M and Lo S 2015 Characterization of thermal decomposition behavior of commercial flame-retardant ethylene–propylene–diene monomer (EPDM) rubber *Journal of Thermal Analysis and Calorimetry* **122** 449
[13] Tsai K 2009 Orientation effect on cone calorimeter test results to assess fire hazard of materials *Journal of Hazardous Materials* **172** 763
[14] Janssens M and Douglas B 2004 Wood and wood products *Handbook of building materials for fire protection* 1
[15] Cachim P B and Franssen J 2009 Comparison between the charring rate model and the conductive model of Eurocode 5 *Fire and Materials* **33** 129