Fire safety and flame-retardant property of representative wood-based composites

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ABSTRACT

This paper considers the mass loss rate, specific extinction area, heat release rate (HRR), effective heat combustion (EHC), total heat release (THR) and ignitability efficiency (IE) as the fire-hazard indices of wood-based composites (WBCs). Fire-retardant dipped paper plays a major role in the flame resistance of WBCs. An optimized cone calorimeter is developed, and the flame-retardant properties of plain and modified WBCs are assessed. The HRR curves reach the wave crest at a high rate with no distinct peaks in the period of 81 s to 320 s. EHC histograms are slightly low, where their increasing tendencies are not apparent within the time range of 110 s-320 s. However, the relatively small THR of modified medium-density fiberboard (MDF) indicates that it emits less heat with a minor fire risk. We conclude that IE follows the order: MDF with dipped paper < plywood with dipped paper < chipboard with dipped paper, with the chipboard showing the largest combustion risk.

Keywords: Fire-retardant dipped paper, wood-based composites, flame-retardant property

1. INTRODUCTION

Fire is valuable in daily life and has a dual character. On the one hand, it affords convenience and warmth to humans. On the other hand, it is associated with destructive combustion hazards[1,2]. Wood-based composites (WBCs) have been widely used in all aspects of human production. However, most of these are flammable and combustible, with low values of limiting oxygen index (LOI); LOI denotes the minimum percentage of oxygen required to maintain the flaming combustion of wood products under laboratory conditions[3-5]. WBCs such as chipboards, medium-density fiberboards (MDFs), plywood and oriented strand boards, are composed of wood chips[6]. They exhibit green and environmentally sustainable advantages that help improve the utilization rate of wood[7]. However, the amount of fire accidents caused by WBCs is also high. When WBCs burn, the heat release rate (HRR) is evidenced by a gradual increase in heat, which is not easy to extinguish[8]. The main factors of casualties and losses in actual fires include heat and smoke from wood combustion and general endangerment to air environments.

In the combustion process, cone calorimetry is a dependability evaluation for the fire safety of wood, which gives the relationship between sample mass, thermal insulation, and exhaust smoke over time[9]. This method shows outstanding advantages for studying the combustion performances of WBCs and provides a means of simulating fire scenes with reasonable models. Under simulated fire conditions, all types of flame-retardant information can reliably supplement and confirm each other, particularly in building and furniture applications[10,11]. Analytical results from energetic combustion experiments contain compositions, structures, and variability of wood. Characterization methods of flame-retardant composites, such as the horizontal/vertical method[12] and NBS smoke method[13], can assess combustion characteristics and flame-retardant mechanisms.

Immersion and hybrid techniques are commonly applied to promote the flame retardancy of WBCs[14,15]. Of these techniques, the immersion technique increases the production cycle with an increase in cost. The hybrid technique has an over-dispersed flame retardancy, which reduces its utilization efficiency. Both techniques require the addition of a large amount of flame retardant; this also negatively impacts the physical and mechanical properties of the WBCs. In this study, we verified a veneering technique in which fire-retardant dipped paper was adhered to WBCs. Flammability tests were then

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performed using a cone calorimeter and smoke density box to analyze the combustion performances of plain and modified WBCs. The mass loss rate (MLR), effective heat combustion (EHC), apex heat release rate (AHRR), and ignitability efficiency (IE) were utilized as fire-hazard indices. We evaluated the flame-retardant properties of representative WBCs and those modified with fire-retardant dipped paper.

2. MATERIALS AND METHODS

2.1 Instruments and materials

A Stanton Redcroft cone calorimeter (UK), Fire Testing Technology Ltd. NBS smoke density box (UK), and Discovery TGA thermogravimetric analyzer (USA) were used in experiments. Commercially available chipboards, MDFs, and plywood of 10 cm × 10 cm × 1.0 cm were purchased from the Zhejiang Wood Research Institute (China). The modified WBCs were prepared referring to the reports in Reference[16]. The fireproof liquid was prepared by a thorough mixing of ammonium polyphosphate/pentaerythritol/melamine/urea resin mixtures. Base paper (0.8-mm thick, 90 $g\cdot m^{-2}$ FAW) was dipped into the as-prepared fireproof liquid for 7 min and then dried in an 80°C vacuum oven to a constant weight. Finally, the fire-retardant dipped paper was adhered to the WBCs.

2.2 Experimental approach

WBCs were weighed in triplicate, and their thicknesses were measured using a Vernier caliper to record average values. Each WBC sample was sealed with tin foil. A thermal radiation heater was used for cone calorimetry to generate radiant flows of different intensities on the wood surfaces. The specimens were ignited using an electric igniter, and the combustion products were collected using a smoke-collecting hood and then discharged outdoors. The smoke was discharged using a collecting hood and pipe at the upper part of the calorimeter. The HRR was calculated from the mass flow and oxygen content. The combustion performance was assessed according to three standards[17,18]: GB 8624-2012 "Classification for burning behavior of building materials and products," and ISO 9705-1-2016 "Reaction to fire tests—Room corner test for wall and ceiling lining products—Part 1: Test method for a small room configuration."

2.3 Fire-hazard index

The following fire-hazard indices were proposed for the flame-retardation specifications of wood. MLR ($g\cdot s^{-1}$) is the rate of mass reduction during pyrolysis. The ignition time (IT, s) is the ignition duration when a luminous flame burns on the material surface. The AHRR ($kW\cdot m^{-2}$) is the maximum rate of heat resulting from the combustion per unit area. The total heat release (THR, $MJ\cdot m^{-2}$) is the heat released per unit area of the composites from the flame's beginning to the time it is extinguished. IE concerns the difficulty of ignition, described by the logarithm of the LOI (%). The specific extinction area (SEA, $m^2\cdot kg^{-1}$) is the smoke production per unit mass during the burning process as shown in equation (1):

$$\mathrm{SEA} = \frac{k \times v}{\mathrm{MLR}} \tag{1}$$

where k is the extinction coefficient (m^{-1}) and v is the volumetric velocity ($m^3\cdot s^{-1}$). Smoke production reflects the exposure level of combustible smoke over time.

3. RESULTS AND DISCUSSION

Prior to each experiment, the WBCs were preserved at a temperature of 23 ± 1°C and relative humidity of 49 ± 2%. Subsequently, the individual flame conditions were then regulated at the level of the above-mentioned calorimetry standards, and wood combustibility tests were conducted using a cone calorimeter (Figure 1). Combustion characteristics were studied, including flame spread and heat release coefficients. In addition, the effects of radiation intensity on combustibles in small-scale fires and the rates of the pyrolysis reaction of WBCs under external heat radiation were investigated.

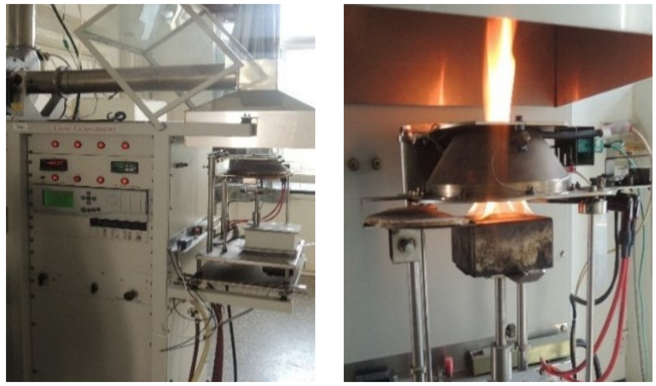

Figure 1. Photos of cone calorimeter used in the wood combustibility tests.

IT plays a major role in assisting people in escaping actual fires, where every minute counts. In our study, when the surrounding radiant flux was continuously heated, the WBCs pyrolyzed. When the gas concentration of the pyrolytic boards reached a critical value, the WBCs began to burn. IT reflects the flammability difference of the materials. As Table 1 shows, the IT of the chipboard, MDF, and plywood was 21s, 27s, and 24 s, respectively. The chipboard ignited more easily, whereas the fitting result of the MDF was better. These three boards were modified with fire-retardant dipped paper under IT of 61 s, 80 s, and 73 s, respectively. Thus, the IT of the modified WBCs was prolonged following surface treatments, which promoted their flame resistance to a certain extent. We determined that the MDFs modified with fire-retardant dipped paper were the best at preventing ignition.

Table 1. IT of plain WBCs and WBCs modified with fire-retardant dipped paper.

Type	Chipboard	MDF	Plywood	Chipboard with dipped paper	MDF with dipped paper	Plywood with dipped paper
IT (s)	21	27	24	61	80	73

The heat release capacity of the fire source sustained wood pyrolysis, and volatile combustibles were formed. As Figure 2 shows, the AHRR of plywood with dipped paper at 213.5 kW·m^{-2} was greater than those of the surface-treated MDF (170.6 kW·m^{-2}) and chipboard (159.8 kW·m^{-2}). The HRR plot of the plywood was unstable for real-time combustion. It was confirmed that the chipboard with dipped paper experienced an earlier ignition point and at a high rate, whereas the overall value of the MDF with dipped paper revealed relatively steady combustion at elevated temperatures.

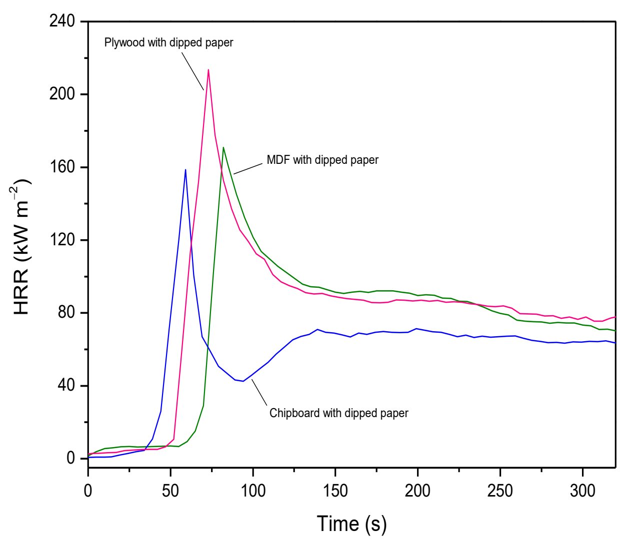

Figure 2. HRR of representative surface-treated WBCs at 15 kW m^{-2} external heat radiation.

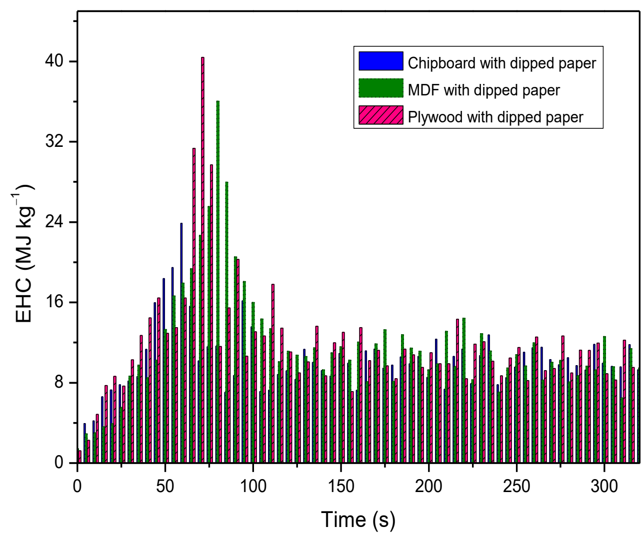

Figure 3. EHC of WBCs modified with fire-retardant dipped paper.

The comparison of HRR curves and EHC histograms (Figure 3) indicated that within the time range of 0-110 s, a considerable number of volatile products were emitted and ignited. The HRR curves of the modified WBCs reached the wave crest at a high rate, and no obvious peaks were present in the range of 81 s-320 s. The fire-retardant dipped inhibitor intervened in the combustion chain reactions, which reduced the oxygen consumption under a given MLR. During the wood-flaming phase, the effective transfer rate of the surface-treated WBCs was slightly low and did not demonstrate a remarkable increase in the later phase (110 s-320 s).

After the WBC surfaces were modified with fire-retardant dipped paper, the THR scatters of the plain chipboard, MDF, and plywood significantly decreased. The THR and flammability of the WBCs exposed to fire were used to further evaluate flame retardancy based on heat propagation (Figure 4). The fluctuations in the THR were statistically derived to obtain the average signals from ingredient residues through the fire-retardant reaction with wood. At the early stage of the burning process (0-73 s), the THR of plywood was lower than those of the MDF and chipboard, but it became greater than those of the other two in the time range of 74 s-320 s. The total heat of the MDF with dipped paper was relatively low, indicating that it emitted less heat and presented only a minor fire risk. In general, the gas-phase reaction route led to the retardancy of nonflammable gas. The resultant nonflammable gas diluted the volatile products and oxygen, thereby suppressing wood combustion.

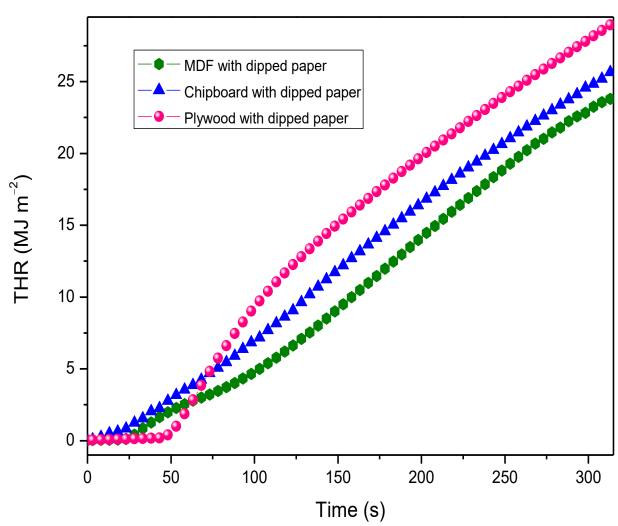

Figure 4. THR of WBCs modified with fire-retardant dipped paper.

Studies on thermal radiation and smoke emission were compared to analyze the flame resistance levels of the materials. The relevant data for the MLR, SEA, and IE are listed in Table 2. Mass and thickness were also classified as the integrated indicators. We presented the calculation results for characterizing the main combustion parameters. MLR was subjected to controlled levels of radiant heating, and the SEA was related to the smoke production capabilities of the outer plates. The IE followed the order of: MDF with dipped paper < plywood with dipped paper < chipboard with dipped paper. Notably, the modified chipboard had the largest combustion risk, whereas the IE of the MDF and plywood when combined with dipped paper were 0.29 and 0.4, respectively. The thermal and smoke effects were not only distinctive features of incendiary composites but also contributed to the selection of WBCs for furniture substrates.

Table 2. Main parameters of combustion characteristics for modified WBCs.

Specification	Mass (g)	Thickness (cm)	MLR (g s^{-1})	SEA (m^2 kg^{-1})	IE
Chipboard with dipped paper	96.5	1.1	0.45	460.11	0.47
MDF with dipped paper	97.3	1.1	0.73	282.53	0.29
Plywood with dipped paper	96.8	1.1	0.61	375.94	0.40

4. CONCLUSION

This work determined that fire-retardant dipped paper plays a major role in the fire safety and flame resistance of WBCs. Plain chipboard, MDF, and plywood were modified with fire-retardant dipped paper with IT of 61s, 80s, and 73s, respectively. The MLR, SEA, EHC, THR, and IE were calculated for flame-retardant evaluation based on the data measured using a cone calorimeter and smoke density box. The total heat of the MDF with dipped paper was relatively low. The IEs of the WBCs followed the order: MDF with dipped paper < plywood with dipped paper < chipboard with dipped paper. Therefore, the chipboard exhibited high oxygen consumption, leading to the largest combustion phenomenon.

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