

# Thermal and burning properties of wood flour-poly(vinyl chloride) composite

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**Abstract** The present study deals with the effects of wood flour on thermal and burning properties of wood flour-poly(vinyl chloride) composites (WF-PVC) using thermogravimetric (TG), cone calorimetry (CONE), and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS). TG tests show that an interaction occurred between wood flour and PVC during the thermal degradation of WF-PVC. Wood flour decreased the temperature of onset of decomposition of PVC. However, the char formation could be increased by adding wood flour to PVC. CONE test indicates that wood flour had positive effects on heat release and smoke emission of PVC. Comparing with PVC, WF-PVC reduced average heat release rate and the peak HRR by about 14 and 28%, respectively; smoke production rate was also decreased. The degradation mechanism was studied by Py-GC/MS. The results show that the volatile pyrolysis products of WF-PVC are very different from PVC. The yields of HCl and aromatic compounds decreased dramatically, and the aliphatic compounds increased by the incorporation of WF.

**Keywords** Wood flour · Poly(vinyl chloride) (PVC) · Wood-plastic composite · Thermal decomposition · Combustion

## Introduction

Fillers are commonly used in the thermoplastic industry to provide stiffness and strength to plastics. Although inorganic fillers such as calcium carbonate, glass fiber, clay, mica, and talc, currently dominate the thermoplastic industry, wood-derived fillers have become more accepted in recent years because of the increased awareness about recycling and the need for lower cost materials. Growth of these materials has averaged more than 25% per year since 1998. No segment of the plastics industry has grown faster [1].

The most commonly used thermoplastics in manufacturing wood-plastic composites (WPCs) are polyethylene (PE) [2–4], polypropylene (PP) [5–7], polystyrene (PS) [8, 9], and polyvinyl chloride (PVC) [10–14]. Among these, the markets for wood flour-poly(vinyl chloride) composites (WF-PVC) are increasing dramatically, with a growth perspective of 200% from 2002 to 2010 [1]. They are now typically used in building construction applications, such as window/door profiles, decking, railing, and siding [11].

However, the properties of WF-PVC may be unsatisfactory if the composites encounter severe thermal and/or chemical degradation [15]. Processors are strongly advised to take special care with PVC/natural fiber composites because both PVC and wood fillers are usually thermally unstable. They can degrade at a higher temperature, and also at a lower temperature if there is a longer melt processing duration. Thermal degradation of WF-PVC leads to poor organoleptic properties, such as odor and color and moreover to deterioration of their mechanical properties. Therefore, studies of the thermal properties are of critical importance to the users of WF-PVC. Previous research [16–20] on thermal decomposition of PVC with cellulose derived materials obtained from municipal solid waste was

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primarily motivated by applications such as alternative resources of energy and chemical raw materials. The research in thermal properties of WF-PVC under specific process temperatures of polymer/natural fiber composites is limited [12, 14, 15, 21]. Djidjelli et al. [12] reported that the onset decomposition temperature decreased with increasing wood flour content and the presence of wood flour decreased the degradation rate. Rocha et al. [21] concluded that wood flours led to materials that possessed higher thermal endurance. However, information on thermal changes of the composites is limited, and mainly focused on the influence of wood fiber content in WF-PVC. The interactions between PVC and wood flour under elevated temperatures are rarely mentioned.

Burning properties of WF-PVC composites is another important topic. Regardless of good flame retardancy of pure PVC due to its high chlorine content (56.8%), flammability of its WF-PVC composites is still a concern because of easy flammability of the high content of wood flour and other low-molecular-mass additives as well as the subsequent thermal degradation [22]. In addition, PVC can generate high levels of black smoke when it is burned [23]. But to our knowledge, there have been few fundamental studies in this field.

In this article, we examined the effect of introducing wood flour into PVC on the flame retardancy, smoke suppression, and thermal degradation of WF-PVC; the mechanism was also studied based on the present and previous results.

## Materials

PVC (type SG-5) with a number average molar mass of 1,000 was supplied by Harbin Huaer Chemical Ltd. Co., Harbin, China. Poplar wood flour (WF) (50–80 mesh size) used as filler and solid poplar wood as a control in combustion testing were purchased from a local timber market. Additives such as dioctyl phthalate, calcium stearate (standard grade), chlorinated polyethylene (CPE), and rare earth heat stabilizer (KB-7) were purchased from a local chemical supplier.

## Compounding

The WF was dried at 105 °C for 6 h just before extrusion to remove any moisture. Dried wood flour, PVC, and other additives were poured into the high-speed mixer and mixed for 5 min. The sample was prepared by mixing 100 parts PVC resin, 60 parts wood flour, 12 parts other additives. Next, WF-PVC and PVC samples were prepared by using a SJSH 30 mm twin-screw/45 mm single-screw extruder system. During the extrusion, the temperatures of the processing zones were from 140 to 180 °C, and the die

temperature was 165 °C. The twin-screw extruder speed was 30 rpm and the single-screw extruder was 8 rpm. Extrusion temperature was kept below 200 °C to avoid decomposition and degradation of wood and PVC.

In the last stage, the extruded WF-PVC composite was pressed to obtain samples for fire retardancy testing. The samples were prepared with the use of the following parameters: pressure 7 MPa, temperature 180 °C and cooling under pressure until solidified. The board specimens for fire tests (by CONE) were 100 × 100 × 4 mm<sup>3</sup>.

## Thermogravimetric analysis

Thermogravimetric tests were performed using a Perkin-Elmer System Pro-6 thermogravimetric (TG) analysis system. The dynamic measurements were carried out in a nitrogen atmosphere from room temperature to 750 °C at a heating rate of 10 °C min<sup>-1</sup>.

## Cone calorimeter tests

The burning properties were conducted on a cone calorimeter (FTT Company, UK) in accordance with ISO 5660-1 (cone calorimeter) at a heat flux of 50 kW m<sup>-2</sup>. All of the samples were laid on a horizontal sample holder, and the samples were protected with a stainless steel grid to prevent bending and expanding during heating.

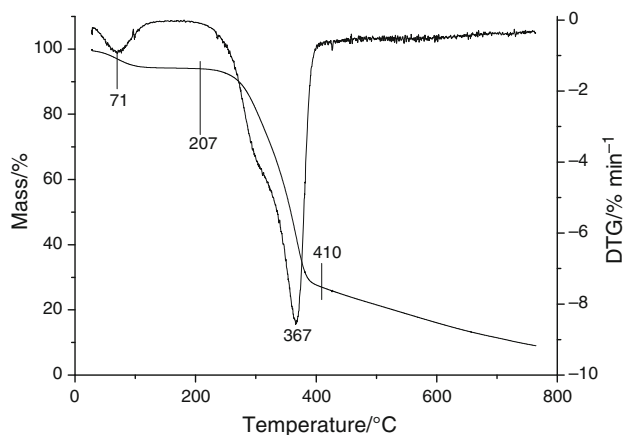
## Pyrolysis–gas chromatography/mass spectrometry

Pyrolysis–gas chromatography/mass spectrometry analysis was tested on a combined system of an Australian SGE pyrolyzer and Agilent 6890N-5793i GC–MS. Pyrolysis temperature was set at 500 °C. GC qualitative analysis was conducted with a DB-17MS fused silica capillary column (30mm × 0.25 mm × 0.25 μm). Helium was used as carrier gas with a flow rate of 1.0 mL min<sup>-1</sup>. The column temperature was held at 40 °C for 5 min, then raised to 240 °C at the rate of 3 °C min<sup>-1</sup> and finally the temperature was kept at 240 °C for 8 min. Injector temperature was 260 °C. The mass spectrometer was operated in EI (Electron Ionization) mode at 70 eV with the scan range between 15 and 500 amu.

## Results and discussion

### Thermal behavior study by TG analysis

The thermogravimetry analysis curves of TG and DTG of WF, PVC, and WF-PVC are shown in Figs. 1, 2, and 3. The main parameters of the thermal degradation process are given in Table 1. In order to conveniently investigate

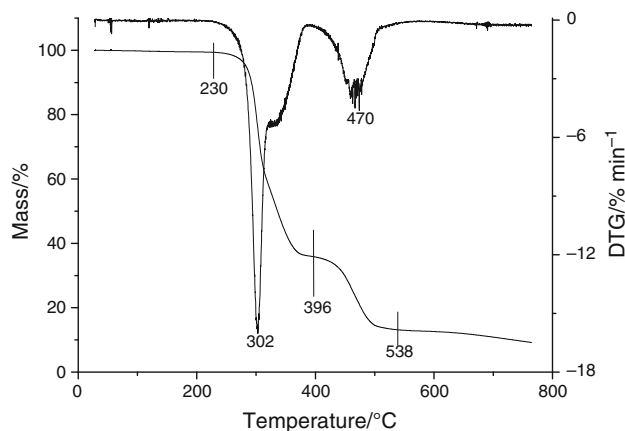


**Fig. 1** TG and DTG curves of WF

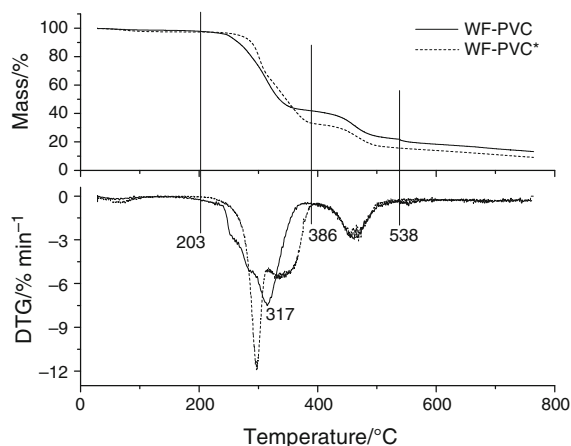
the effect of WF on the thermal properties of PVC, PVC and additives were considered an integrated system.

From Fig. 1, the TG and DTG curves of WF recorded in this study are similar to the curves obtained by other authors [24, 25]. Thermal degradation of wood can be divided into three stages. The initial low temperature mass loss corresponds to loss of moisture and it is a common feature observed for lignocellulose fibers [24, 26]. No degradation took place and WF was considered as thermally stable at this stage. For the second stage, rapid mass loss occurred in the temperature range 207–410 °C. The mass loss was about 67% (see Table 1). The second stage corresponds to the main decomposition process and proceeds at a high rate. It can be attributed to the thermal decomposition of hemicelluloses and cellulose [25, 27–30]. After the second stage, mass losses of the residual materials of WF were slow. At this stage, the residue decomposed at a very slow rate and carbon-rich residual solid formed [27]. According to DTG spectra, WF had a small and broad DTG peak at 70 °C and a big and sharp peak at around 367 °C. The latter peak had a broad base and showed a shoulder peak at about 309 °C, the lower temperature peak could be attributed to the decomposition of hemicellulose [24], although the values obtained in this study were higher than the usual range attributed to hemicellulose thermal decomposition from 260 to 281 °C [30].

For PVC (Fig. 2), there were two mass loss stages. The sample was thermally stable for temperatures below 230 °C. Decomposition started at about 230 °C and ended around 396 °C in the first stage. During this decomposition stage the sample mass loss dropped drastically (63.5% mass loss in Table 1), due to the volatilization of hydrogen chloride molecules (HCl) [23, 31]. This process, going on along the macromolecules, may lead to conjugated polymeric chains [12]. From 396 °C to 538 °C, a second decomposition stage was observed, much shorter than the first one and corresponding to the thermal cracking of the



**Fig. 2** TG and DTG curves of PVC



**Fig. 3** TG and DTG curves of WF-PVC and WF-PVC\*

carbonaceous conjugated polyene sequences [23]. From DTG, a big and sharp peak occurred at 302 °C and a small and broad peak at about 470 °C. The second stage was recorded as a single peak whereas in the dehydrochlorination stage, a slight shouldered peak in the reaction rate was observed. This behavior was also observed by others [32, 33]. It was suggested to be due to the different mechanisms of thermal degradation of the PVC, which seem to be significantly dependent on the morphology [32].

Similar to PVC, WF-PVC composite also revealed a two-stage degradation (Fig. 3). The first stage was in the temperature range about 203–386 °C, while the second stage was from about 386 to 538 °C. WF-PVC\* is the result calculated by adding WF and PVC results based on their percentages in the composite. WF-PVC does not coincide with the calculated WF-PVC\* curve. Compared with WF-PVC\*, WF-PVC decomposed early which is in agreement with the literature [12, 21]. WF seems to accelerate the initial degradation of PVC matrix in composites. The reduced degradation temperature of the composite may result from the influence of the acids generated

**Table 1** Thermogravimetric analysis data under pure nitrogen

Samples	$T_{\text{onset}}/^{\circ}\text{C}$	First stage			Second stage			Residue at 700 $^{\circ}\text{C}$ %
		Temperature range/ $^{\circ}\text{C}$	$T_{\text{max}}/^{\circ}\text{C}$	Mass loss %	Temperature range/ $^{\circ}\text{C}$	$T_{\text{max}}/^{\circ}\text{C}$	Mass loss %	
WF	207	28–135	71	5.6	207–410	367	67	11.4
PVC	230	230–396	302	63.5	396–538	470	22.7	10.9
WF-PVC	203	203–386	317	55.7	386–538	462	20	15.2
WF-PVC*	210	210–386	299	63.7	386–538	468	17.9	11.1

from the wood. Lewis acids, as well as inorganic or organic acids can increase the rate of dehydrochlorination of PVC [23]. It is known that wood can generate formic acid, acetic acid, and glyoxal at the initial temperature below 250  $^{\circ}\text{C}$  when heated [34]. These products of WF at low temperature could accelerate the initial dehydrochlorination of the PVC and reduce the degradation temperature.

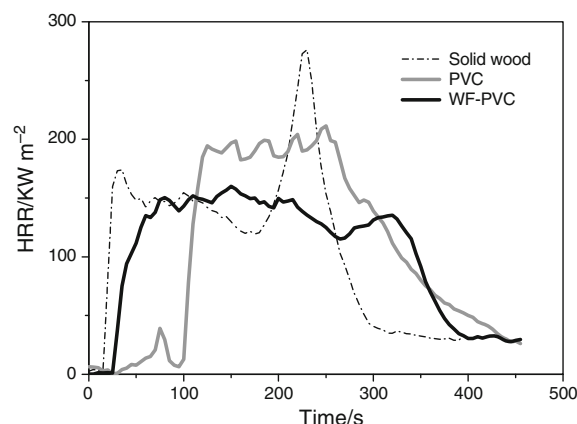
The significant interaction can be clearly observed from DTG curves of WF-PVC and WF-PVC\*. Shapes and sizes of WF-PVC and WF-PVC\* in the first major stage are very different while in the second stage are almost the same. It can be concluded that the interaction mainly occurred in the first stage. In the absence of interaction between WF and PVC, two composite peaks of WF and PVC were presented in WF-PVC\*; in the first stage, the first peak was the characteristics of PVC (volatilization of hydrogen chloride molecules), while the second peak was from WF (decomposition of hemicellulose and cellulose). However, WF-PVC showed one DTG peak in the first stage, PVC and the WF peaks in WF-PVC\* overlapped and shifted somewhat compared with those feature peaks of WF and PVC, respectively. The temperature at maximum peak of the thermal degradation of PVC in the mixtures is higher than that of pure PVC, while the peak degradation temperature of WF in the mixtures is lower than that of pure WF. This was believed to be caused by some interaction of HCl with the cellulose and hemicellulose due to the first step of decomposition of PVC occurring in the same temperature range as for the hemicellulose and cellulose fractions of WF. Kuramochi et al. [19] observed that hemicelluloses served as strong Cl absorbents resulting in fixing HCl emission at the char form. It is probable that wood flour accelerated the elimination of HCl from PVC macromolecule forming conjugated double bonds  $\text{C}=\text{C}$ . These bonds will eventually cyclize and then eventually char. Meanwhile, HCl from PVC has a significant effect on thermal decomposition and charring of wood. Detailed effect mechanism of PVC on WF was studied by Matsuzawa et al. [17]. In the presence of hydrogen chloride, a decrease in hydroxyl groups and an increase in  $\text{C}=\text{C}$  and  $\text{C}=\text{O}$  bonds in the mixture were indicated by FT-IR. HCl evolution

from PVC may thus possibly function as an acid-catalyst to promote the production of dehydration and charring by cleavage of glucosidic units and cross-linkages.

The above analysis demonstrates that HCl played an important role in char formation of the composite and wood promotes the crosslinking and char formation of PVC though the elimination reaction of HCl; moreover, HCl that comes from PVC can promote the dehydration and charring of wood. It is confirmed by the data in Table 1, that the amount of residual char obtained from experiments is larger than the calculated value. This result indicates that the thermal degradation of WF-PVC composite is a complex process as a result of the interaction between PVC and WF. The addition of WF into PVC had a positive effect on thermal performance of the composite.

#### Flammability of the composite by cone calorimetry

The flammability parameters were conducted on a cone calorimeter, which is considered to be a good facility for studying fire degradation, smoke emission, and heat release [35]. In the present article, time to ignition (TTI), heat release rate (HRR), total heat released (THR), effective heat of combustion (EHC), mass loss rate (MLR), char

**Fig. 4** Curves of HRR of samples

residue (CR), smoke production rate (SPR), total smoke release (TSR), and the yield of CO and CO<sub>2</sub> were obtained.

TTI, HRR, THR, and EHC are important parameters for evaluating flame retardancy and flammability of polymeric materials, while MLR, CR, SPR, and TSR could help the understanding of the extent of the mass loss and smoke generation during combustion. Another important parameter that helps the understanding of the fire hazard related to materials is the emission of toxic gases. The toxicity of gaseous products from the combustion of materials is determined by the emission of CO accompanied by CO<sub>2</sub>. These parameters describe flammability and smoke emission behaviors of WF-PVC in Figs. 4, 5, 6, and 7. The typical values are summarized in Tables 2 and 3.

### Heat release

PVC is itself a flame retarded polymer because of a high content of chlorine. However, it still releases some heat when forced to burn. The main parameter measured in cone calorimeter is HRR, which is considered by Hirschler [36] to be the most important parameter for evaluating fire behavior of materials. Figure 4 shows HRR curves of the samples and other heat release values are presented in Table 2.

Because WF-PVC is a composite material, we expect its fire performance characteristics to fall somewhere between that of PVC and wood. From Table 2, it can be seen that the TTI based on cone calorimetry of WF-PVC fell between that of PVC and solid wood. The addition of WF to PVC decreased the time necessary for inflammation when compared to PVC, from 102 to 26 s. This observation appears to be in agreement with the TG mass loss results reported above, in which the addition of WF reduced the degradation temperature, thus increasing the ease of ignition. Although the presence of WF brings about an earlier ignition of WF-PVC composite, the process of combustion proceeds at a significantly lower HRR. Compared to PVC and wood, WF-PVC reduced the average HRR (av-HRR) and the peak HRR (pk-HRR) by about 14, 28% and 12, 42%, respectively. This can be clearly seen from HRR curves in Fig. 4.

**Table 2** Cone calorimetric heat release data at 50 kW m<sup>-2</sup>

Parameter/unit	Sample		
	Solid wood	PVC	WF-PVC
TTI/s	14	102	26
av-HRR/kW m <sup>-2</sup>	115.8	118.2	99.6
Pk-HRR/kW m <sup>-2</sup>	276.2	221.3	159.9
THR/MJ kg <sup>-1</sup> sample	11.61	7.60	9.42
av-EHC/MJ kg <sup>-1</sup>	12.47	8.83	10.36

In Fig. 4, three distinguishable HRR curves were observed. HRR data correspond directly to the intensity of fire. Wood shows a typical double pk-HRR curve. The first sharp peak comes soon after ignition and a second peak appears near the end of the flaming combustion period. The first peak results from the initial release of volatiles, while the second peak in the HRR curve results from the char layer breaking down and contracting, thus producing small cracks on the surface [37]. These cracks facilitate the escape of volatiles that combust and result in the observed increase in HRR. Compared to wood, PVC shows one plateau after ignition, then gradually decreased at the end of burning. HRR value of WF-PVC composites is the lowest among in all samples. The wood flour promoted the very rapid ignition of the sample so the jump in HRR is earlier than in PVC. However, after the ignition, the presence of wood flour in PVC resulted in a consistent and lower HRR value at a moderate level. It may be due to the formation of an insulating char layer, which makes heat transfer more difficult, thus slowing the pyrolysis process. It is interesting that the wood flour gave some increment in total heat release of PVC during the combustion. This indicates the volatiles produced burn easily, which is further confirmed by EHC obtained from the cone calorimeter.

EHC represents the heat released per unit mass of materials being volatilized during flaming. It is considered to be an important parameter to evaluate the flammability of volatiles produced during burning. Curves of EHC are shown in Fig. 5, and the results of the average effective heat of combustion (av-EHC) are listed in Table 2. PVC had a lower av-EHC than wood. HCl evolved in burning of PVC is a scavenger of radicals in the gas phase resulting in low burning efficiency of PVC. In Fig. 5, we can see PVC had an even and low EHC value at a moderate level after ignition, with an increase just before the end of the flaming. EHC curve of WF-PVC is very close to PVC at the beginning of the burning. However, it increased to a higher level than that of PVC at the end of the combustion. This result probably indicates the formation of less vapor-phase aromatics, which are poorly combustible and potent smoke

**Table 3** Cone calorimetric mass loss and smoke emission data at 50 kW m<sup>-2</sup>

Parameter/unit	Sample		
	Solid wood	PVC	WF-PVC
av-MLR /g s <sup>-1</sup>	0.082	0.118	0.085
CR/%	17.2	15.2	19.0
TSR/m <sup>2</sup> m <sup>-2</sup>	172	4161	3658
CO yield/kg kg <sup>-1</sup>	0.015	0.088	0.084
CO <sub>2</sub> yield/kg kg <sup>-1</sup>	1.53	0.80	1.06

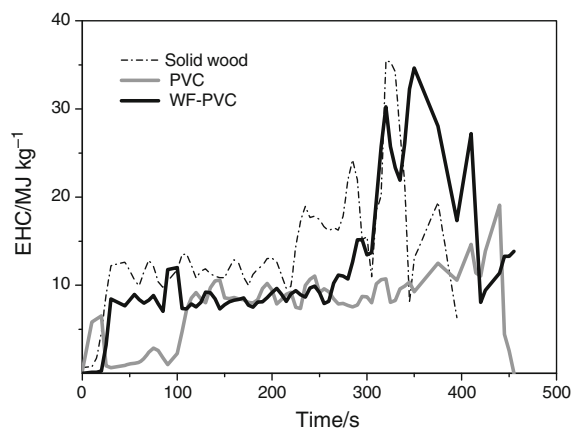


formers. Thus, combustion is reduced overall, but the burning that does occur is more efficient.

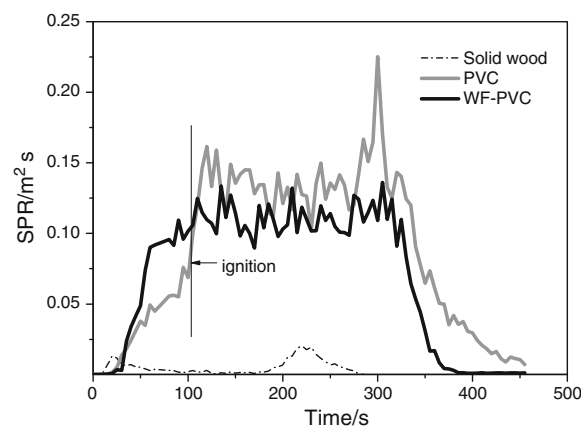
### Smoke production

In PVC based composites, smoke production is usually the most important concern, and research usually is directed toward smoke suppression in PVC, rather than fire retardancy. The curves showing the evolution of smoke with time are provided in Fig. 6, and the smoke data are shown in Table 3. TSR value of WF-PVC composite in Table 3 was reduced by 12.1% compared with that of PVC. It demonstrates that wood flour also has a positive effect on smoke suppression.

Figure 6 shows the curves of SPR with time. When PVC burns, it pyrolyzes to form HCl and volatile organic (aromatic) compounds, which evolve large amounts of smoke. Therefore, SPR of PVC is higher than for wood. In general, the combustion process of materials can be divided into three steps: (1) non-flaming mode appearing before ignition, (2) flaming mode, and (3) after-glowing mode. The smoke emission occurs in both the non-flaming step and the flaming step, while there is no smoke evolved in the after-glowing step [38]. This result is of great significance in understanding the smoke emission of PVC and WF-PVC. Figure 6 clearly shows the first two combustion steps of PVC on the basis of the time scale. The first step in the smoke emission process is the fog of elimination of HCl without heat release, while the second step is mainly the black particles that have volatilized from the aromatic condensed phase. Compared to PVC, the curve of WF-PVC is higher than PVC in the first step, while it is lower than PVC in the second step. It has been discussed that the incorporation of wood flour shortens the ignition time of PVC, thus the elimination of HCl is earlier. An apparent key to limiting PVC smoke formation is minimizing the formation of volatile fuels through crosslinking, which



**Fig. 5** Curves of effective heat of combustion



**Fig. 6** Curves of SPR of samples

produces nonvolatile char [39]. As the burning proceeds, a char layer may be formed resulting in a decrease in SPR value in comparison with PVC. It will be discussed later in the mass loss.

The data for CO and CO<sub>2</sub> production values can be seen in Table 3. CO and CO<sub>2</sub> are generated when PVC burns. Compared with PVC sample, wood flour showed little effect on CO and CO<sub>2</sub> production level.

### Mass loss and MLR

Heat release and smoke emission must be compared to the data on mass loss. Mass loss is a reflection of thermal decomposition behavior during burning and plays a very important role in heat release and smoke emission. Combined with TG analysis, it can give a better understanding of thermal decomposition and degradation.

As can be seen in Fig. 7, at the heat flux of 50 kW m<sup>-2</sup>, MLR curve of PVC did not clearly show the thermal decomposition processes (HCl elimination reaction and thermal degradation of carbon chain) which is described in the TG. This is probably due to the fact that the higher incident heat flux used in the cone calorimeter is sufficient to counteract the effect of volatiles on the fire performance of the PVC. But it can be confirmed that the mass loss before the ignition during the combustion was mainly caused by the HCl elimination reaction. Because, the volatiles evolved in this stage cannot be ignited even if the MLR is large. In fact, it has been well proven that HCl acts as a scavenger of radicals in the gas phase [40]. At the start of combustion of WF-PVC, MLR is higher than for PVC; the presence of wood flour promotes the elimination of HCl from PVC, which is consistent with the TG analysis. Wood flour reduces MLR at the end of the combustion, indicating that the wood flour can inhibit the thermal decomposition of carbon chain of PVC by the crosslinking of PVC backbone and thus promote char formation at a high incident heat flux of 50 kW m<sup>-2</sup>.

A comparison of MLR curves, HRR curves (Fig. 4), and SPR curves (Fig. 6) can give a better understanding of the flame retardancy and smoke suppression of the samples. It is noted that the shape of MLR curve of wood is similar to that of HRR curve, while PVC acts more like SPR curve. It demonstrates that wood transformed most of the mass loss into heat, thus increased the burning efficiency, while PVC transformed most of the mass loss into smoke. However, the curve shape of the MLR of WF-PVC is different from that of HRR or SPR. As mentioned earlier, the addition of WF contributes to the char formation, which is considered to be a reason for flame retardancy and smoke suppression. From the data of the residues percent in Table 3, the residues of WF-PVC composites were 21.3% higher than for PVC. The results showed that the wood flour in WF-PVC composites promote char formation.

#### Thermal pyrolysis process analysis by Py-GC/MS

To find evidence how wood flour promotes the crosslinking and char formation, and then decreases the heat release and smoke emission of PVC, the thermal mechanism degradation of the PVC and WF-PVC composites was further investigated by Py-GC/MS.

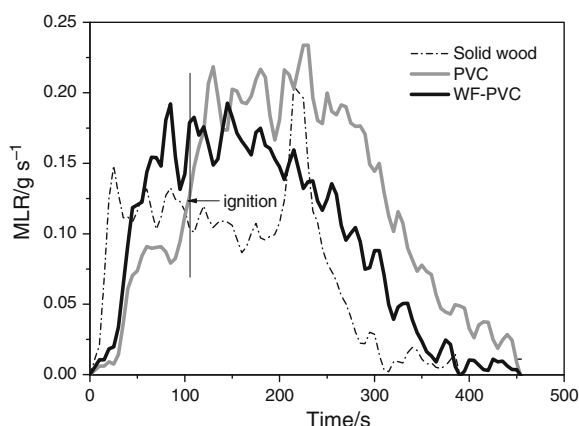
The principle pyrolysis products of PVC and WF-PVC at 500 °C are listed in Table 4. In order to interpret the results obtained, pyrolysates were grouped on the basis of their chemical characteristics. For PVC, the most abundant volatile pyrolyzate was a series of aromatic compounds (that account for about 59.56% of the pyrogram). More than 30 aromatic compounds were identified, the most concentrated being benzene and its substituents, followed by polycyclic aromatic hydrocarbons, such as naphthalene, methylnaphthalenes, biphenyl, indene, fluorene anthracene, and chlorobenzene at trace levels. All these products have been identified in the pyrolysate of PVC and related

**Table 4** Principle identified pyrolysis products of PVC and WF-PVC

Product of pyrolysis	Percent of total area %	
	PVC	WF-PVC
Aromatic compounds	59.56	7.27
Aliphatic compounds	2.49	38.58
HCl	25.7	8.74
Acids and their derivatives	6.39	12.97
Esters	4.25	17.17
Aldehydes	0.3	10.86
Alcohols	0.14	2.18
H <sub>2</sub> O and CO <sub>2</sub>	2.02	3.35

polymers [31, 41–43]. As we discussed in TG analysis, these volatile aromatic compounds arose from the elimination of HCl (dehydrochlorination), followed by cyclization-aromatization reactions of resulting conjugated polymeric chains.

Compared to PVC, the presence of wood flour greatly decreased the amounts and components of aromatic products, the content of the aromatic products decreased from 59.6 to 7.7%, and only seven identified aromatic products were monitored in WF-PVC. As the amount of aromatic products decreased, the aliphatic products increased appreciably. The content of aliphatic products in WF-PVC composites is about fifteen times than that in PVC (from 2.49 to 38.8% in Table 4). It has been discussed that the char formation increased by the addition of wood flour. According to Mantaudo and Puglisi [44], the crosslinking to produce char and decompose to produce aromatics were two competing processes. Changes of the pyrolysates provided insight into the mechanism by which the addition of wood flour changed the degradation pathways of PVC in the direction of promoting charring. In addition, HCl that arose in the earliest stages of dehydrochlorination of PVC was greatly decreased, which indicated that wood flour took effect mainly by catalyzing dehydrochlorination of PVC, then promoting early crosslinking to lead to rapid charring. It clarifies why WF-PVC exhibits better thermal and combustion performance than PVC. Meanwhile, aromatic compounds were considered to be a main reason for producing smoke than aliphatic compounds when PVC is burnt, which further explained the reason for smoke reduction in WF-PVC.



**Fig. 7** Curves of MLR of samples

#### Conclusions

Thermal and combustion properties of WF-PVC composite were investigated by means of TG and CONE analysis. The

results obtained in this study allow us to draw the following conclusions:

- (1) Thermal analysis results indicated strong interaction between PVC and WF. The addition of WF into PVC matrix significantly accelerates initial dehydrochlorination of the PVC, but retards the PVC thermal decomposition based upon the char increase. This indicates that WF promotes the crosslinking and char formation of PVC through the elimination reaction of HCl. Moreover, HCl evolution from PVC may function as an acid-catalyst of WF at high temperature.
- (2) The cone calorimetry test confirms that WF shortens the time necessary for inflammation of PVC; it promoted the combustion of WF-PVC composite. However, it has a positive effect on heat release and smoke suppression. Little effects on CO and CO<sub>2</sub> output levels were observed.
- (3) WF can accelerate the char formation of PVC during burning. The residues of WF-PVC were 21.3% more than for PVC, which is considered to be a reason for lower heat release and smoke suppression.
- (4) Mechanisms for the effects of WF on WF-PVC composites are further confirmed by Py-GC/MS. The thermal degradation pathways of PVC may be changed by the addition of WF due to the facts that the aromatic compounds decreased and aliphatic compounds increased.

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