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# Pyrolysis Characteristics of Wood-Based Panels and its Products

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## Abstract

Wood-based panels containing urea formaldehyde (UF) resin will be focused on to make clear the influence of UF resin on pyrolysis products and transformation mechanism during pyrolysis of waste wood composites. Thermogravimetric analysis (TGA) will be used to study the thermal degradation reaction kinetics according to different heating rate. Thermogravimetric analyzer coupled to a Fourier transform infrared spectrometer analysis (TGA-FTIR), X-ray photoelectron spectroscopy (XPS) and gas chromatography coupled with mass spectrometry (GCMS) will be used to study the gas, solid, liquid products, respectively. Results from TG and differential thermogravimetric analysis (DTG) indicate that UF resin at first accelerated the degradation rate however inhibited the degradation of wooden composites over the whole pyrolysis process. Compared with wood, UF resin had an obvious effect on the release of H<sub>2</sub>CO and NH<sub>3</sub>. Mass loss of hydrogen is significantly inhibited by UF resin and nitrogen is much stable in the char with structure of the pyridine and pyrrole at relative content of 6.65% and 7.45% respectively. Influence of UF resin on pyrolysis liquids of wooden composites is mainly on nitrogen compounds and ketones rather than aldehydes and esters, which is probably due to the chemical reactions of UF resin with lignin constituent in wood.

**Keywords:** wood-based panels, pyrolysis characteristic, reaction kinetics, pyrolysis products

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## 1. Introduction

Considering energy and resources, major conventional fossil energy resources are at the verge of extinction. Biomass as a renewable resource has been explored as the substitute of conventional energy and chemical resources. As a kind of lignocellulosic bioresource, waste

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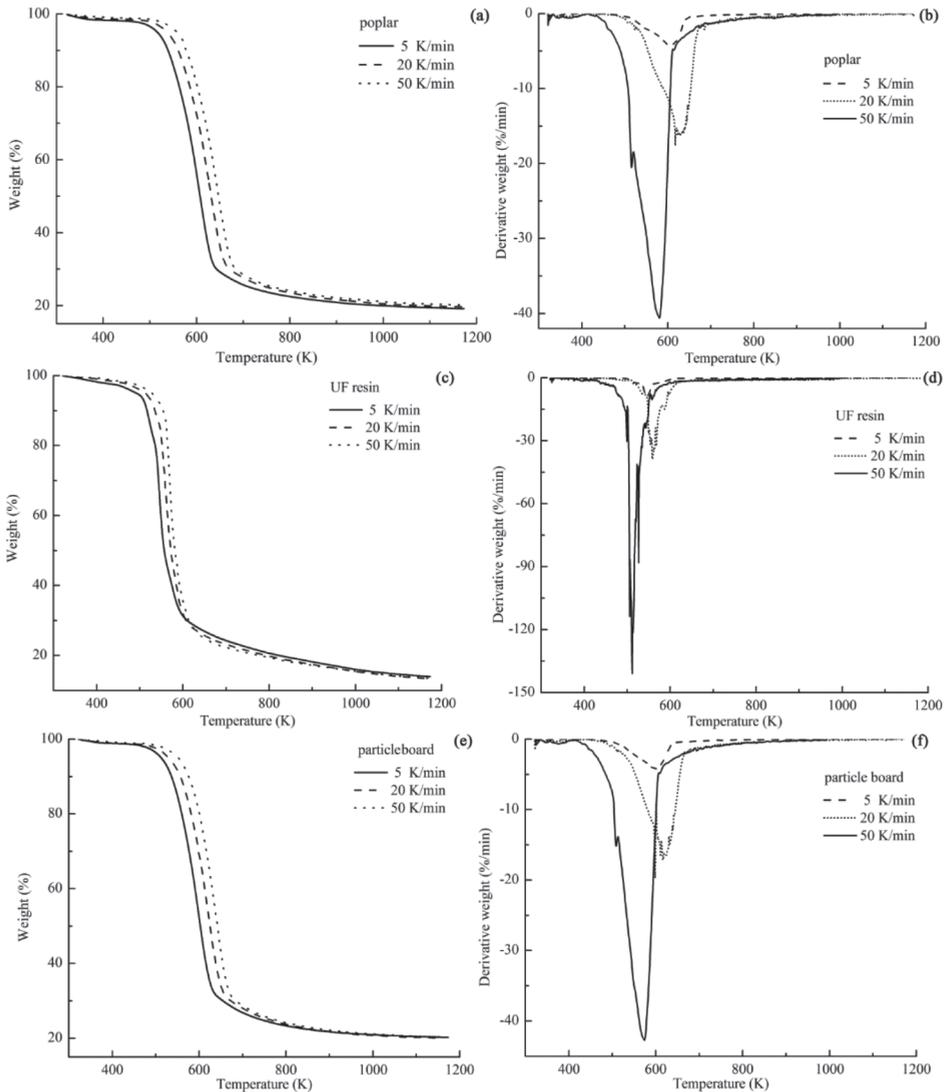
wood-based panels show great potentials to provide raw materials for the production of renewable fuels and chemical feedstocks. Hence, it is of great significance for the efficient utilization of wood-based panels to better understand the thermal decomposition mechanism of wood-based panels and its products distribution.

## 2. Pyrolysis characteristics of wood-based panels

Nowadays, the main utilization method of waste wood-based panels is through incineration. Although this method can convert waste wood-based panels into energy, owing to the existence of formaldehyde-based adhesives, it is inevitable to release N-containing gases during the combustion process, which could lead to air pollution. Thermal-chemical processes including pyrolysis, gasification, and hydrogenolysis have proven to be a highly efficient process to utilize bioresource including waste wood-based panels. Because of formaldehyde-based adhesives, characteristics and products of pyrolysis of wood-based panels are much different from that of common bioresource and the influence of resins should be investigated.

### 2.1. Influence of adhesives on conversion of biomass

In order to study the pyrolysis characteristics of wood-based panels, the pyrolysis of main components of wood-based panels has been studied using a thermogravimetric technique. Most of the research results show that the wood, urea formaldehyde (UF) resin, and wood-based composites all show three steps of weight loss, weight loss with elevated temperature, as presented in **Figure 1**. In the first stages, moisture lost from the material and trace weight loss could be found in all samples because samples were predried before thermal analysis. The second stage is the most significant decomposition stage during the whole process, with most of weight loss. During the second stage, the main release of primary volatiles, a charring process that consists in the rearrangement of char skeleton, occurs. The third stage is mainly the slow decomposition of the residual part, without obvious quality change, leading to the formation of char. This behavior is quite common in biomass samples. The samples present a single, broad peak of decomposition. The majority weight loss of UF resin is in an active step over a range of about 180–330°C. Pyrolysis of UF resin produces higher yield of volatile matters compared to wood. This result may be caused by structure difference between them. The UF resin has a network, which mainly consists of groups of imino, carbonyl, and methylene. Pyrolysis of poplar particleboard produces more char and less volatile matter compared to its two components, which means that the thermal behavior of poplar particleboard is not the reflection of the sum of the behavior of poplar and UF resin. UF resin is more likely to accelerate the chemical reactions of wood-based panels at lower temperature, however, inhibited the degradation of solid residue of wood-based panels at higher temperature during the global pyrolysis process. The thermal stability of UF resin is weaker than wood; however, it enhanced the thermal stability of wood-based panels, which confirms former conclusions.



**Figure 1.** TG curves of poplar (a), UF resin (c) and particleboard (e); and DTG curves of poplar (b), UF resin (d) and particleboard (f) at three different heating rates [1].

## 2.2. Influence of adhesives on conversion of biomass components

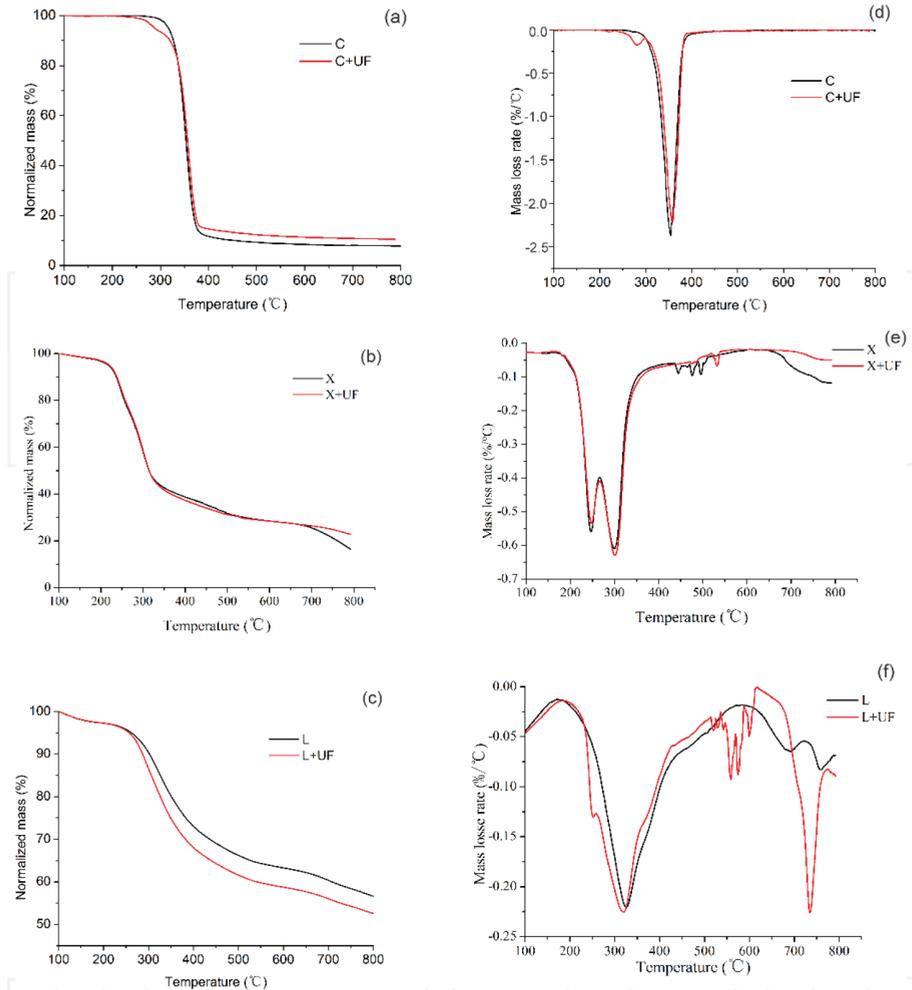
UF resins and modified urea-formaldehyde (MUF) resins have poor thermal stability. A study on pyrolysis of urea formaldehyde resins suggested three reactions resembling wood pyrolysis involved in the pyrolysis, which were initiation reactions, reactions splitting off volatile matters, and reactions forming stabilized structure [2]. Due to the existence of adhesives,

characteristics and products distribution of pyrolysis of wood-based panels are different from that of common bioresource and the influence of resins should be investigated.

Cellulose, hemicellulose, and lignin are the main components of biomass, which consist of more than 90% of wood. Given the complexity of wood-based panels, pyrolysis conversion, and the diversity of the obtained products, it may be more convenient to study separately the conversion of each constituent. Based on the research of the main components separately, and the pyrolysis behavior of wood-based panels can be assumed as the sum of the main components weighted summatively.

In this section, the pyrolysis of each of the main biomass components mixed with UF resin is individually discussed. First, the results from the literature concerning thermogravimetric analysis are used to detail the main steps of conversion. The influence of UF resin on the three main biomass constituents is different, as illustrated in **Figure 2**. The results obtained from TG analysis show that three reaction stages involved in the pyrolysis before or after mixed with UF resin. However, the DTG curves representing the mass loss rate of a constituent generally present a different profile with several peaks after addition of UF resin. It is clear that the TG curve of cellulose adding UF resin moved to the higher temperature range after 200°C. Meanwhile, the maximum weight loss rate of cellulose pyrolysis was decreased. So the UF resin is more likely to inhibit the degradation of cellulose after 200°C especially in the suppression of the pyrolysis rate. Former researcher [3] indicated that an acidic environment may accelerate the dehydration reaction of the cellulose. While the alkaline environment caused by UF resin was assumed to be the main reason to inhibit the degradation of cellulose. For xylan (representative of hemicellulose), TG and DTG curves before and after mixed with UF resin generally coincided. So the UF resin had little influence on the pyrolysis behavior of the hemicellulose. For lignin, TG curves added UF resin moved to the low temperature segment after 200°C. With the addition of UF resin, the char yield reduced and the maximum mass loss rate slightly increased. Therefore, the promotion of UF resin in the process of pyrolysis for the lignin after 200°C can be observed. While the promoting effect plays a more evident role in weight loss rather than the degradation rate. It can be concluded that during the process of the pyrolysis of waste wood-based panels, lignin was the one that UF resin mainly impacted among the three main components of wood.

Innovatively, the weight-loss character of the model (made from cellulose, xylan, and lignin, based on the chemical components study of poplar wood), the main components as well as the ones mixed with UF were analyzed by TG-FTIR. According to the results from TG analysis, the residual weight of poplar and model is very close, and the weight loss curve is basically the same. It can be seen that the model has similar pyrolysis characteristics to common biomass. The TG curves show that the UF resin has obvious effects on the pyrolysis of the model. In the TG analysis, it is well known that the two curves coincide basically before 250°C, the differences appear gradually after 250°C. Studies realized that UF resin could promote the pyrolysis of model on the basis of a small diminution in char yield [4].



**Figure 2.** TG and DTG curves of cellulose (C), xylan (representative component of hemicellulose, X) and lignin (L) as well as the ones mixed with UF resin [4].

### 2.3. Kinetic study

There are variety of models available for analyzing the kinetics of the investigation of biomass thermal decomposition, including first-order [5], discrete activation-energy distributions [6], and sequential models [7] such as models having Gaussian [8], Weibull [9], and Gamma [10] distributions. The distributed activation energy model (DAEM), representing the sequential models, has been employed successfully for analyzing complex reactions in thermal decomposition of biomass. The model assumes that an infinite number of first-order parallel

reactions having unique kinetic parameters take place concurrently. The kinetic parameters could be calculated through thermogravimetric analysis (TGA) without considering complex chemical reactions during a thermal decomposition process [11]. The representative equation for the Miura-Maki model [12] is

$$\ln\left(\frac{\beta}{T^2}\right) = \ln\left(\frac{k_0 R}{E}\right) + 0.6075 - \frac{E}{RT} \quad (1)$$

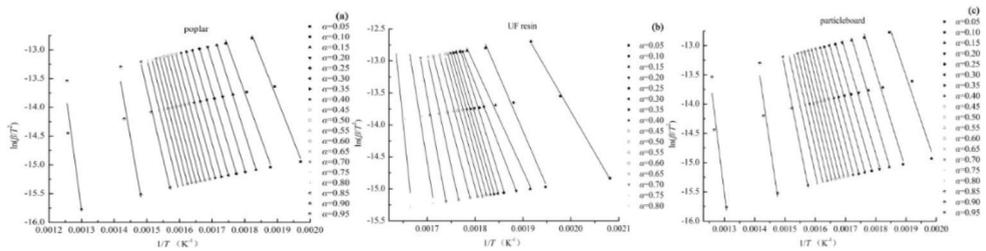
To investigate this further, based on the pyrolysis of particleboard, the kinetic parameters were calculated. Zhang et al. [1] reported the plots of  $\ln(\beta/T^2)$  versus  $1/T$  at selected  $\alpha$  for poplar, UF resin and particleboard, as presented in **Figure 3**. For every value of  $\alpha$ , the three points corresponding to the three heating rates are positioned in a straight line, as the method predicts. The sum of the pyrolysis behavior of poplar and UF resin cannot embody the thermal behavior of poplar particleboard. The activation energy of poplar and particleboard is 140–200 kJ/mol; however, the activation energy of UF resin is 150–300 kJ/mol, and that the activation energy of particleboard is lower than that of the poplar during the main pyrolysis stage because of the promoting effect of UF resin.

### 3. Influence of adhesives on pyrolysis products distribution of biomass

Pyrolysis is a capital step of biomass thermochemical conversion as it is the first step of all the process. Biomass by the action of heat in an inert atmosphere can be converted into gas, char, and a liquid composed of a mixture of hundreds of oxygenated organic compounds [13, 14]. More precise information about conversion mechanisms of wood-based panels is provided by coupling TG analysis and on-line analyzer of the evolved products such as FTIR. With this approach, it is possible to study the composition of the evolved products throughout the temperature rise of the sample. Based on the evolution of the structure of the gas products, we can have better understanding of the evolution of the composition of the sample. What is more, the knowledge of formation of the evolved compounds helps to understand the reactions of fragmentation of unstable functions during the main pyrolysis stage and of rearrangement during the charring process [15]. Moreover, the X-ray photoelectron spectroscopy (XPS) technique can be used to probe the chemical changes occurring in the solid residue prepared by pyrolysis, the GC-MS technique can be also used to analyze the composition of the pyrolysis liquid condensed from volatile matters of the pyrolysis of wood-based panels, additional information can be obtained. Based on a review of the study of our team and other authors, the influence of adhesives on the formation of products (char, liquid, gas) can be described.

#### 3.1. Gas

Owing to the complexity of biomass conversion, few authors tried to explain the influence adhesives on the chemical reactions involved at the molecular scale. The study of the volatile matters obtained from the pyrolysis of wood-based panels mainly concentrates on N-containing gases, such as  $\text{NH}_3$ , HCNO, and HCN. For a better understanding of these mechanisms,

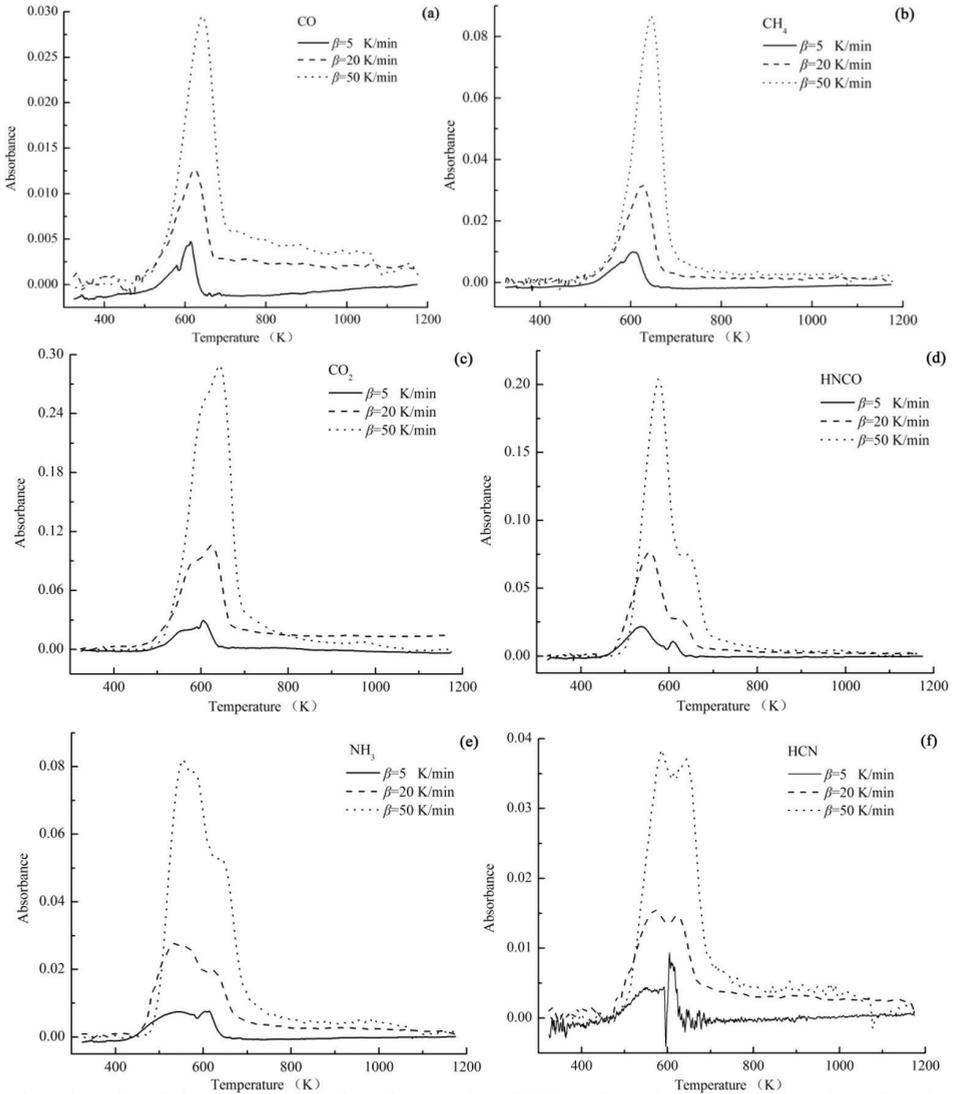


**Figure 3.** Plots of  $\ln(\beta/T^2)$  versus  $1/T$  of poplar (a), UF resin (b), and particleboard (c) at different conversion rates [1].

based on a review of the published research works, the influence of the adhesives on the formation of these products is discussed.

The volatile matters obtained from the pyrolysis of wood-based panels and common bioresource contain  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{NH}_3$ ,  $\text{HCNO}$ , and  $\text{HCN}$  [16–18]. However, as presented in **Figure 4**, N-containing gases of the pyrolysis of common bioresource derived from the decomposition of extractives in wood, nitrogen gases of the pyrolysis of wood-based panels are significantly influenced with the addition of UF resin. It is concluded that the degradation of urea function in UF resin generates  $\text{HNCO}$  and a precursor of  $\text{HCN}$ , which will crack into  $\text{HCN}$  (the gas is highly toxic, when conducting experiments, operators should be very careful) under  $650^\circ\text{C}$  [19]. In regard to  $\text{NH}_3$ , we could make conclusions that the fragmentation of UF resin unit directly leads to the formation of azyli at the narrow temperature range between  $180$  and  $320^\circ\text{C}$  and then the formation of large quantities of  $\text{NH}_3$  with the highest intensity at  $210^\circ\text{C}$  [17]. A small amount of  $\text{CH}_4$ ,  $\text{CO}$ , and  $\text{CO}_2$  could also be detected gradually at the low temperature range, which is primarily due to the break of the methoxyl group and single C–C bonds. According to the literature [3, 20], it is assumed that  $\text{CH}_4$ ,  $\text{CO}_2$ , and  $\text{CO}$  are formed, respectively, by the cracking of methoxy groups, decarboxylation, and decarbonylation. In the main pyrolysis stage, the break of carboxyl in the lateral chains in furfural acid results in the release of  $\text{CO}_2$ . The less stable carbonyl in volatiles is more likely to be the precursor of  $\text{CO}$ . The formation of  $\text{CO}$  is also largely influenced by second cracking of volatiles during the thermal process [21]. During the third pyrolysis stage in a high temperature range between  $400$  and  $800^\circ\text{C}$ , almost all the gases reach their equilibrium intensity value, which is relatively low. Lignin degradation plays an important role in this stage. Functional groups in the lateral chains of phenyl propane are still cracking and volatiles would undergo further secondary reactions, resulting in the formation of incondensable gas and of small chain organic compounds.

TG-FTIR analysis of each of the main biomass components mixed with UF resin can explicitly understand the influence of UF resin on the formation of gas products. Cellulose is a linear homopolysaccharide of cellobiose monomers, composed of C, H, and O. Hence, the element N of the nitrogen gases obtained from the pyrolysis of UF-cellulose blend only results from the pyrolysis of UF resin. The addition of UF promoted the formation of water and carboxylic acids during cellulose pyrolysis. The study of Shafizadeh and Bradbury [22] showed that the pyrolysis process of cellulose is divided into two stages. Below  $300^\circ\text{C}$ , reducing the degree



**Figure 4.** Evolutions of CO (a), CH<sub>4</sub> (b), CO<sub>2</sub> (c), HNCO (d), NH<sub>3</sub> (e), and HCN (f) level in pyrolysis product during pyrolysis of particleboard at three different heating rates [1].

of polymerization caused by bond breaking leads to the formation of free radicals (carbonyl radicals, carboxyl radicals, and hydroperoxyl radicals), the release of H<sub>2</sub>O, CO, and CO<sub>2</sub>, depolymerization induced by transglycosylation appears at 300°C or above. The influence of UF resin on the pyrolysis of cellulose is mainly in the low temperature range, namely the first stage of cellulose pyrolysis. UF resin promotes the fracture of chemical bonds in cellulose and accelerates the formation of carbonyl and hydroxyl radicals. For lignin, UF resin could

promote the release of CO during the pyrolysis process. The interaction between UF resin and lignin leads to the formation of weak stable compounds, then releases large amounts of nitrogen compounds and oxycarbides. The influence of UF resin on wood-based panels could be found mainly in the release of nitric gases. Intensity peaks of nitric gases of wood-based panels are higher and occur earlier than that of wood. Therefore, UF resin is the main factor contributing to the nitric gases of the pyrolysis of waste wood-based panels while the influence on the CO<sub>2</sub> is not obvious.

### 3.2. Char

Char formation consists in the conversion of biomass in a solid residue, namely char, which presents an aromatic polycyclic structure [23, 24]. Intra- and intermolecular rearrangement reactions occurred in the process of char formation could result in a higher degree of reticulation and in a higher thermal stability of the residue [23, 25]. The significant steps of these reactions are the formation of benzene rings and the combination of these rings in a polycyclic structure. Recombination consists in the combination of volatile compounds lead to the formation of a higher molecular weight molecule, which sometimes is no longer volatile matter under the conditions of temperature of the reactor [26, 27]. When the recombination happens inside the pores of the polymer, this reaction can lead to the information of a secondary char.

The char of wood-based panels obtained from pyrolysis also contains C, H, N, and O. The content of these elements in the char is different from wood-based panels. The content ratio of C in sample is relatively stable both before and after pyrolysis. Although a large amount of element C are lost, C is still the main element in the char, accounting for 70–90%, and the mass loss of these elements could be influenced by UF resin. The influence of UF resin on element C is not significant; however, the mass of element O is the largest one, probably fixed in the form of oxygenated compounds in pyrolysis liquid and CO, CO<sub>2</sub> in gases during process. In contrast of content in original sample, it could be found that UF resin inhibited the loss of H mostly during pyrolysis; however, there was no significant relationship between the loss of element H and the content of UF resin in wood-based panels. The content of N is relatively steady both before and after pyrolysis of particleboard with little changes in each sample, while the content of N in medium density fiberboard (MDF) decreases dramatically. This difference originates probably from the different interactions between UF resin and different lignocellulosic materials. A study on pH value of the char of wood and wood-based panels display as neutral and alkaline; therefore, it is concluded that the element N in UF resin is also retained in the char of wood-based panels.

To investigate this further, the X-ray photoelectron spectroscopy technique was used to research the existing forms of nitrogen compounds in char of wood-based panels, as presented in **Table 1**.

The main form of element N in MDF is primary amine (399.4 eV), and some are amide (399.8 eV). The main form of element N in wood is amide (399.8 eV), which originates from the protein existed in wood extractives. Meanwhile, amide (399.8 eV) is the main form of element N

in UF resin, accounting for 32.69%. Both of UF resin and MDF have strong intensities of peaks attributed to the C-N stretching vibration ( $1690\text{--}1590\text{ cm}^{-1}$ ). However, the structure of primary and amide is not detected in the samples after pyrolysis. The existing forms of nitrogen compounds in MDF char were pyridine (398.4 eV) and pyrrole (400.2 eV). In the pyrolysis process, the N-containing compounds undergo bond cleavage and rearrangement to form stable cyclic structures of pyridine and pyrrole.

### 3.3. Liquid

Biomass mainly consists of cellulose, hemicellulose, and lignin, and therefore its pyrolysis behaviors as the integrated performance of these three components [29]. Given the complexity of lignocellulosic material and of biomass pyrolysis conversion, the liquid products obtained from pyrolysis of biomass consist of complex chemical compositions, including acids, alcohols, aldehydes, ketones, and esters [30, 31] and have higher oxygen content and lower heating value than hydrocarbons. Furthermore, its acidity, high water content, and corrosion make it hard to be used as a transportation fuel [32]. In general, the physicochemical properties of pyrolytic products are closely related to future industrial applications. The compositions of pyrolysis liquid of wood-based panels are of obvious difference from those produced from biomass. The pH value of pyrolysis liquid of common bioresource always is shown as acidity, while that of pyrolysis liquid of wood-based panels varied from acidity to alkalescency. These difference occurred in the two types pyrolysis liquid originates from the existence of UF resin in the wood-based panels and conditions for thermal decomposition. And furthermore, the variation of pH value of pyrolysis liquid of wood-based panels may be due to the types of wood-based panels and pyrolysis conditions. The specific gravity of pyrolysis liquid of wood-based panels is relatively stable, varying from 1 to 1.1 [33, 34]. The specific gravity of pyrolysis liquid also is influenced by pyrolysis conditions, such as pyrolysis temperature and the heating rate. The different compositions of pyrolysis liquid of wood-based panels compared to common bioresource are mainly on the nitrogen compounds. The relative content of nitric compounds in pyrolysis

Samples	Relative amount (%)					
	Binding energy (eV)	399.4	399.8	398.4	400.2	403
	Chemical structure	Primary amine	Amide	Pyridine	Pyrrole	Pyrrole oxide
Original samples	MDF	4.28	1.07	/	/	/
	Wood fiber	/	0.49	/	/	/
	UF	/	32.69	/	/	/
Char	MDF	/	/	6.65	7.45	0.4
	Wood fiber	/	/	0.24	0.71	/
	UF	/	/	1.36	2.29	/

**Table 1.** Contents of different N constructions of wood fiber, MDF, and UF resin [28].

liquids of wood is very few but different types of amides are detected in pyrolysis liquids of wood-based panels and UF resin. The formation of nitric compounds in pyrolysis liquids originates from the conversion of urea in UF resins as applied in wood-based panels and the interaction between UF resin and wood [1]. The transformation of nitrogen-containing compounds is influenced by the interactions between UF resins and wood constituents. From GCMS analysis of the pyrolysis liquid of UF resin, it can be found that nitrogenous substances are the main components. Feng et al. reported that the two most abundant components in pyrolysis liquids of UF resin are methyl-urea and N, N'-dimethyl-urea [17], while Zhang et al. reported that the most relative content is N-ethylformamide [1]. In addition, other nitrogenous substances, such as 1-Methyl-2,4,5-trioximidazolidine, 2,3-Pyridinediamine, Pyrimidine,5-methyl-, urea, formyltrimethyl-, can also be detected in the pyrolysis liquid of UF resin. Nitrogen-containing heterocyclic compounds in the pyrolysis liquid of UF resin, such as pyridine, pyrimidine and piperazine, are alkaline and have irritating smell (see **Table 2**).

The anhydro-saccharides identified correspond to glucose-derived compounds undergone several dehydration reactions. Glycosidic bond cleavage of cellulose and aldol condensation reaction lead to the formation of 1,6;2,3-Dianhydro-4-O-acetyl-beta-D-gulopyranose and 2,3-Anhydro-D-mannosan. Furan derivatives are considerable constituents of pyrolysis liquid of biomass. These furan derivatives are generated by the pyrolysis of holocellulose. These compounds can also be considered as depolymerization products. Various kinds of ketones are detected in pyrolysis liquids, which are probably formed by decarboxylation with active chemical properties. Ketones are much likely to be originated from the large amount of carbonyls in wood. Some pyridone, imidazolone in the form of nitrogen heterocyclic compounds are found in pyrolysis liquids of wood-based panels but little are found in UF resin, suggesting that nitrogen from UF resin is reformed and fixed with chemical groups degraded from wood in the form of ketones in the pyrolysis liquids.

During the pyrolysis process, lignin molecule chains are splitted and fragments are rearranged, and pyrolysis products are mainly phenolic compounds. Phenolic compounds in pyrolysis liquids of particleboard (PB) are mainly originated from lignocelluloses; however, their structures might be influenced by UF resin in terms of nitrogen during the thermal conversion process, resulting in a small amount of phenol (peak area around 1.5%) in PB despite the large amount (peak area over 15%) detected in pyrolysis liquids of wood. The influence of UF resin on other components including aldehydes, alcohols, and esters is not significant since these compounds are not the main components in pyrolysis liquids of PB and not detected in pyrolysis liquids of UF resin.

The influence of UF resin for particleboard is mainly on the nitrogen compounds, as presented in **Table 3**. There is a small amount of nitric compounds in the pyrolysis liquid of wood. However, a large number of nitrogenous compounds in the pyrolysis liquid of wood-based panels are detected, such as pyrimidine,5-methyl- and 1,3,5-triazine-2,4,6(1H,3H,5H)-trione,1,3,5-trimethyl-, just generated by the pyrolysis of UF resin. But others generated by the concerted reaction of wood and UF resin, such as 4-(1H)-pyridinone,2,3-dihydro-1-methyl. Thus, it can be seen that the transformation of nitrogen-containing compounds in the process of wood pyrolysis is influenced by the interactions between UF resin and wood.

As the main constituent in wood, cellulose will go through dehydration reaction during pyrolysis process, forming levoglucosan and glycolaldehyde. The glucosyl groups will then crack into smaller structures in high temperature. Research studies show that acids could catalyze the dehydration reactions while UF resin introduces an alkaline atmosphere during the pyrolysis, which inhibits further cracking of glucosyl groups. Compared with cellulose, hemicelluloses are inhomogeneous glycan with weaker thermal stability. The pyrolysis of

Retention time (min)	Designation	Molecular formula	Relative amount (%)
3.30	Acetonitrile	$C_2H_3N$	0.54
3.51	N-ethylformamide	$C_3H_7ON$	54.52
5.12	Pyrimidine,5-methyl-	$C_5H_6N_2$	4.50
6.59	1H-imidazole,1-methyl-	$C_4H_6N_2$	1.18
8.66	Cyclohexanol,3-methyl-	$C_7H_{14}O$	0.30
9.92	Urea, formyltrimethyl-	$C_5H_{10}O_2N_2$	4.30
10.16	Pentanamide, N-(aminocarbonyl)-	$C_6H_{12}O_2N_2$	0.88
10.72	3,4-Pyridinediamine	$C_5H_7N_3$	1.81
11.07	N-N'-dimethylamide	$C_4H_8O_2N_2$	1.26
13.45	1H-imidazole[1,2-b] pyrazole,2,3-dihydro-	$C_5H_7N_3$	0.19
13.62	(1H)-Pyrrole-3- carbonitrile,2-methyl-	$C_6H_6N_2$	0.13
13.79	Hydrouacil,1-methyl-	$C_5H_8O_2N_2$	1.40
14.22	2,3-Pyridinediamine	$C_5H_7N_3$	6.79
15.68	Piperazine,1-methyl-	$C_5H_{12}N_2$	0.86
16.01	Hexahydroindole	$C_8H_{13}N$	1.63
17.07	2-Acetyl-3-methyl-3,4,5,6- tetrahydropyridine	$C_8H_{13}ON$	0.50
18.36	1,3,5- Triazine-2,4,6(1H,3H,5H)- trione,1,3,5-trimethyl-	$C_6H_9O_3N_3$	2.38
18.49	S-triazolo[4,3-A] pyridine,8-amino-	$C_6H_6N_4$	2.03
19.81	1-Methyl-2,4,5- trioximidazolidine	$C_4H_4O_3N_2$	7.65
21.20	1,2,4-Trizolo[4,3-A] pyridin-8-amine,3-methyl-	$C_7H_8N_4$	2.70
22.94	6-Methyl-7,8- dihydro-2(1H)-pteridinone	$C_7H_8ON_4$	1.75
24.46	2-Pyrrolidinophenol	$C_{10}H_{13}ON$	2.69

**Table 2.** Main components of pyrolysis liquid of urea formaldehyde resin [1].

Retention time (min)	Designation	Molecular formula	Relative amount (%)
4.55	2-Furanmethanol	C <sub>5</sub> H <sub>6</sub> O <sub>2</sub>	14.22
5.29	Acetamide,N,N-dimethyl-	C <sub>4</sub> H <sub>9</sub> ON	1.84
5.68	2-Cyclopenten-1-one,2-methyl-	C <sub>6</sub> H <sub>8</sub> O	0.14
6.03	1-Pyrrolidinecarbonitrile	C <sub>5</sub> H <sub>8</sub> N <sub>2</sub>	11.24
7.39	2-Cyclopenten-1-one,3-methyl-	C <sub>6</sub> H <sub>8</sub> O	2.33
7.58	4-Aminopyrimidine	C <sub>4</sub> H <sub>5</sub> N <sub>3</sub>	0.50
8.09	Pyrimidine,5-methyl-	C <sub>5</sub> H <sub>6</sub> N <sub>2</sub>	3.19
8.98	2-Cyclopenten-1-one,2-hydroxy-3-methyl-	C <sub>6</sub> H <sub>8</sub> O <sub>2</sub>	1.45
9.22	2-Sec-butyl-3-methyl-1-pentene	C <sub>10</sub> H <sub>20</sub>	3.19
9.27	2-Cyclopenten-1-one,2,3-dimethyl-	C <sub>7</sub> H <sub>10</sub> O	0.77
9.51	DL-citrulline	C <sub>6</sub> H <sub>13</sub> O <sub>3</sub> N <sub>3</sub>	3.25
9.64	Piperidine,1-methyl-	C <sub>6</sub> H <sub>13</sub> N	0.02
9.88	Phenol,2-methyl-	C <sub>7</sub> H <sub>8</sub> O	0.92
10.68	Ethanone,1-(2-methyl-1-cyclopenten-1-yl)-	C <sub>8</sub> H <sub>12</sub> O	6.64
10.82	1,3-Cyclopentanedione,4-ethyl-	C <sub>7</sub> H <sub>10</sub> O <sub>2</sub>	0.71
10.94	2,5-Pyrrolidinedione,1-methyl-	C <sub>5</sub> H <sub>7</sub> O <sub>2</sub> N	0.62
11.05	1-H-Pyrazole,1,3,5-trimethyl-	C <sub>6</sub> H <sub>10</sub> N <sub>2</sub>	0.21
11.37	1,3-Cyclopentanedione,2,2-diethyl-	C <sub>7</sub> H <sub>10</sub> O <sub>2</sub>	2.12
11.56	Maltol	C <sub>6</sub> H <sub>6</sub> O <sub>3</sub>	1.91
11.69	2-Cyclopenten-1-one,3-ethyl-2-hydroxy-	C <sub>7</sub> H <sub>10</sub> O <sub>2</sub>	1.17
11.85	Bicyclo(2,2,2)octane,2-methyl-	C <sub>9</sub> H <sub>16</sub>	0.10
12.18	4-(1H)-Pyridinone,2,3-dihydro-1-methyl-	C <sub>6</sub> H <sub>9</sub> ON	2.12
12.99	1H-Imidazole,2,4,5-trimethyl-	C <sub>6</sub> H <sub>10</sub> N <sub>2</sub>	0.03
13.36	4,5-Octanedione	C <sub>8</sub> H <sub>14</sub> O <sub>2</sub>	2.04
13.6	Phenol,2-methoxy-4-methyl-	C <sub>8</sub> H <sub>10</sub> O <sub>2</sub>	0.68
13.68	Quinuclidine-3-ol	C <sub>7</sub> H <sub>13</sub> ON	0.15

Retention time (min)	Designation	Molecular formula	Relative amount (%)
13.83	S-triazolo[4,3-a]pyrazine,3-methyl-	C <sub>6</sub> H <sub>6</sub> N <sub>4</sub>	1.31
14.1	2-Hydroxy-3,5-diethyl-5-methylcyclopent-2-en-1-one	C <sub>10</sub> H <sub>16</sub> O <sub>2</sub>	0.55
14.39	1,2-Benzenediol	C <sub>6</sub> H <sub>6</sub> O <sub>2</sub>	1.39
14.51	2-Isopropoxyphenol	C <sub>9</sub> H <sub>12</sub> O <sub>2</sub>	0.68
14.69	Oxazole,4-ethyl-2,5-dimethyl-	C <sub>7</sub> H <sub>11</sub> ON	0.95
14.81	2-Methyl-4-(1-methylethyl)-2-cyclohexenone	C <sub>10</sub> H <sub>16</sub> O	0.57
15.01	Phenol,2,6-dimethoxy-	C <sub>8</sub> H <sub>10</sub> O <sub>3</sub>	0.22
15.64	1,2-Benzenediol,3-methoxy-	C <sub>7</sub> H <sub>8</sub> O <sub>3</sub>	3.53
15.89	1,2-Benzenediol,3-methyl-	C <sub>7</sub> H <sub>8</sub> O <sub>2</sub>	1.15
16.27	Pyridine,4-(1-pyrrolidinyl)	C <sub>9</sub> H <sub>12</sub> N <sub>2</sub>	0.45
16.86	1,2-Benzenediol,4-methyl-	C <sub>7</sub> H <sub>8</sub> O <sub>2</sub>	1.73
18.07	Phenol,2,6-dimethoxy-	C <sub>8</sub> H <sub>10</sub> O <sub>3</sub>	11.67
18.22	Benzenemethanol,3-hydroxy-5-methoxy-	C <sub>8</sub> H <sub>10</sub> O <sub>3</sub>	1.58
18.65	1,3,5-Triazine-2,4,6-(1h,3h,5h)-trione,1,3,5-trimethyl-	C <sub>6</sub> H <sub>9</sub> O <sub>3</sub> N <sub>3</sub>	2.28
19.07	2,3-Dimethylhydroquinone	C <sub>8</sub> H <sub>10</sub> O <sub>2</sub>	0.36
19.14	1,3-Benzenediol,4-ethyl-	C <sub>8</sub> H <sub>10</sub> O <sub>2</sub>	0.27
20.36	1,2,3-Trimethoxybenzene	C <sub>9</sub> H <sub>10</sub> O <sub>3</sub>	3.11
20.44	Ethanone,1-(2,3,4-trihydroxyphenyl)	C <sub>8</sub> H <sub>8</sub> O <sub>4</sub>	1.14
21.41	Ethanone,1-(4-hydroxy-3-methoxyphenyl)-	C <sub>9</sub> H <sub>10</sub> O <sub>3</sub>	0.18
21.64	8-Quinolinol,5-amino-	C <sub>9</sub> H <sub>8</sub> ON	0.27
22.21	Benzene,1,2,3-trimethoxy-5-methyl-	C <sub>10</sub> H <sub>14</sub> O <sub>3</sub>	1.52
22.38	2-Propanone,1-(4-hydroxy-3-methoxyphenyl)-	C <sub>10</sub> H <sub>12</sub> O <sub>3</sub>	0.49
22.54	2-(2-Aminoethyl)-4-amino-6-dimethylamino-s-triazine	C <sub>7</sub> H <sub>14</sub> N <sub>6</sub>	0.14
22.82	4(1H)-Pteridinone,2-amino-	C <sub>5</sub> H <sub>5</sub> ON <sub>5</sub>	0.23
23.98	Phenol,2,6-dimethoxy-4-(2-propenyl)-	C <sub>11</sub> H <sub>14</sub> O <sub>3</sub>	0.23

Retention time (min)	Designation	Molecular formula	Relative amount (%)
24.13	Benzene,1,1'-propylidenebis	C <sub>15</sub> H <sub>16</sub>	0.20
24.53	5-Oxohexanenitrile	C <sub>6</sub> H <sub>9</sub> ON	0.18
25.1	Butan-2-one,4-(3-hydroxy-2-methoxyphenyl)-	C <sub>11</sub> H <sub>14</sub> O <sub>3</sub>	0.33
25.44	2-Pyrrolidinophenol	C <sub>10</sub> H <sub>13</sub> ON	0.72
26.26	Phenol,2,6-dimethoxy-4-(2-propenyl)-	C <sub>11</sub> H <sub>14</sub> O <sub>3</sub>	0.40
26.79	Ethanone,1-(4-hydroxy-3,5-dimethoxyphenyl)-	C <sub>10</sub> H <sub>12</sub> O <sub>4</sub>	0.45
27.34	Benzoic acid,4-hydroxy-3,5-dimethoxy-,hydrazide	C <sub>9</sub> H <sub>12</sub> O <sub>4</sub> N <sub>2</sub>	0.14

Table 3. Main components of pyrolysis liquid of particleboard [1].

xylan in hemicelluloses releases acids and aldehydes products, which are not significantly influenced by UF resin. Lignin is the only aromatic constituent in wood with very complex structures while in UF resin most structures are linear and network linkages. However, many of detected nitrogen compounds show aromatic properties, such as pyridine and pyrimidine. It could be concluded that concerted reactions between UF resin and lignin occur in the pyrolysis process so that lignin is probably the mostly influenced constituent by UF resin in wood.

#### 4. Conclusion

From TG and DTG results, it is found that UF resin in wood-based panels make them to degrade easily at the beginning of thermal treatment but inhibit the degradation of wood-based panels during the second and third stages. Pyrolysis of wood-based panels produces more char and less volatile matters compared to its two components, which indicates that the thermal behavior of poplar particleboard is not just the reflection of the sum of the behavior of poplar and UF resin. The activation energy of both wood and UF resin is higher than the activation energy of wood-based panels during the main pyrolysis stage. The pyrolysis nitrogen gases of wood-based panels were mainly HCN, HCNO, and NH<sub>3</sub>. The experimental results showed that the existing form of nitrogen compounds in MDF was a mesh structure of large molecules. The existing forms of nitrogen compounds in MDF char were pyridine and pyrrole. The influence of UF resin on pyrolysis liquid of wood-based panels is mainly on nitrogen compounds. More nitrogenous compounds are detected in the pyrolysis liquid products.

According to the existing research and practice, pyrolysis liquid of wood could improve the physical and chemical properties and fertility of soil and promote plant growth. The pyrolysis liquids of wood-based panels contain a high content of nitric compounds, besides those

degraded from the main components of wood. Nitrogen is one of a large number of elements, which plant needs and plays an important role in plant growth. The pyrolysis liquids of wood-based panels with UF resin can also inhibit the growth of mold and bacteria [35]. But the application of pyrolysis liquid of wood-based panels in agriculture is still a new subject, worth exploring.

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## References

- [1] Zhang Y, He Z B, Xue L, et al. Influence of a urea–formaldehyde resin adhesive on pyrolysis characteristics and volatiles emission of poplar particleboard. *RSC Advances*, 2016, 6(16):12850-12861.
- [2] Hirata T, Kawamoto S, Okuro A. Pyrolysis of melamine–formaldehyde and urea–formaldehyde resins. *Journal of Applied Polymer Science*, 1991, 42(12):3147-3163.
- [3] Rowell R. The Chemistry of solid wood. *Wood Science & Technology*, 1985, 19(19):17-18.
- [4] Li S J, Chen S H, Mu J. Influence of UF resin on pyrolysis characteristics of biomass components: A thermogravimetric study. *International Conference on Biobase Material Science and Engineering (BMSE)*, 2012, Changsha, China.
- [5] Kissinger H E. Variation of peak temperature with heating rate in differential thermal analysis. *Journal of Research of the National Bureau of Standards*, 1956, 57(4):217-221.
- [6] Burnham A K, Braun R L. Global kinetic analysis of complex materials. *Energy & Fuels*, 1999, 13(1):1-22.
- [7] Braun R L, Burnham A K. Analysis of chemical reaction kinetics using a distribution of activation energies and simpler models. *Energy & Fuels*, 1987, 1(2):153-161.
- [8] Anthony D B, Howard J B. Coal devolatilization and hydrogasification. *AIChE Journal*, 1976, 22(4):625-656.

- [9] Lakshmanan C C, White N. A new distributed activation energy model using Weibull distribution for the representation of complex kinetics. *Energy & Fuels*, 1994, 8(6):1158-1167.
- [10] Astarita G. Lumping nonlinear kinetics: Apparent overall order of reaction. *AIChE Journal*, 1989, 35(4):529-532.
- [11] Ferrara F, Orsini A, Plaisant A, et al. Pyrolysis of coal, biomass and their blends: Performance assessment by thermogravimetric analysis. *Bioresource Technology*, 2014, 171C(2):433-441.
- [12] Miura K. A new and simple method to estimate  $f(E)$  and  $ko(E)$  in the distributed activation energy model from three sets of experimental data. *Energy & Fuels*, 1995, 9:302-307.
- [13] Garcia-perez M, Chaala A, Pakdel H, et al. Characterization of bio-oils in chemical families. *Biomass & Bioenergy*, 2007, 31(4):222-242.
- [14] Evans R J, Milne T A. Molecular characterization of the pyrolysis of biomass. 1. Fundamentals. *Energy Fuels*, 1987, 1:123-137.
- [15] Collard F X, Blin J. A review on pyrolysis of biomass constituents: Mechanisms and composition of the products obtained from the conversion of cellulose, hemicelluloses and lignin. *Renewable & Sustainable Energy Reviews*, 2014, 38(5):594-608.
- [16] Girods P, Dufour A, Rogaume Y, et al. Thermal removal of nitrogen species from wood waste containing urea formaldehyde and melamine formaldehyde resins. *Journal of Hazardous Materials*, 2008, 159(2-3):210-221.
- [17] Feng Y S, Mu J, Chen S H, et al. The influence of urea formaldehyde resins on pyrolysis characteristics and products of wood-based panels. *Bioresources*, 2012, 7(4):4600-4613.
- [18] Li S J, Mu J, Zhang Y. Influence of urea formaldehyde resin on pyrolysis of biomass: A modeling study by TG-FTIR. *Spectroscopy & Spectral Analysis*, 2014, 34(6):1497-1501(5).
- [19] Girods P, Dufour A, Rogaume Y, et al. Comparison of gasification and pyrolysis of thermal pre-treated wood board waste. *Journal of Analytical & Applied Pyrolysis*, 2009, 85(1):171-183.
- [20] Gao N, Li A, Quan C, et al. TG-FTIR and Py-GC/MS analysis on pyrolysis and combustion of pine sawdust. *Journal of Analytical & Applied Pyrolysis*, 2013, 100(6):26-32.
- [21] Li X. Research advance on mechanism of biomass pyrolysis and gasification. *Advances in Fine Petrochemicals*, 2009, 10(10): 45-50.
- [22] Shafizadeh F, Bradbury A G W. Thermal degradation of cellulose in air and nitrogen at low temperatures. *Journal of Applied Polymer Science*. 1979, 23(5):1431-1442.
- [23] Mcgrath T E, Chan W G, Hajaligol M R. Low temperature mechanism for the formation of polycyclic aromatic hydrocarbons from the pyrolysis of cellulose. *Journal of Analytical & Applied Pyrolysis*, 2003, 66(1):51-70.

- [24] Pastorova I, Botto R E, Arisz P W, et al. Cellulose char structure: A combined analytical Py-GC-MS, FTIR, and NMR study. *Carbohydrate Research*, 1994, 262(1):27-47.
- [25] Scheirs J, Camino G, Tumiatti W. Overview of water evolution during the thermal degradation of cellulose. *European Polymer Journal*, 2001, 37(5):933-942.
- [26] Hosoya T, Kawamoto H, Saka S. Pyrolysis behaviors of wood and its constituent polymers at gasification temperature. *Journal of Analytical & Applied Pyrolysis*, 2006, 78(2):328-336.
- [27] Morf P, Hasler P, Nussbaumer T. Mechanisms and kinetics of homogeneous secondary reactions of tar from continuous pyrolysis of wood chips. *Fuel*, 2002, 81(7):843-853.
- [28] Chen S H, Li S J, Mu J. Conversion characteristics of urea formaldehyde resin adhesive in fiberboard through pyrolysis into solid product. *Journal of Beijing Forestry University*, 2013, 35(4):123-127.
- [29] Xu S Y, Chen J J, Cao D R. Analysis of components in wood vinegar. *Guangzhou Chemistry*, 2006, 31(3):28-31.
- [30] Branca C, Paola Giudicianni A, Blasi C D. GC/MS characterization of liquids generated from low-temperature pyrolysis of wood. *Industrial & Engineering Chemistry Research*, 2003, 42(14):3190-3202.
- [31] Yaman S. Pyrolysis of biomass to produce fuels and chemical feedstocks. *ChemInform*, 2004, 45(31):651-671.
- [32] Lappas A A, Samolada M C, Iatridis D K, et al. Biomass pyrolysis in a circulating fluid bed reactor for the production of fuels and chemicals. *Fuel*, 2002, 81(16):2087-2095.
- [33] Mu J, Yu Z M, Zhang D R, et al. Pyrolysis characteristics of disused composite panels and properties of its products. *Journal of Beijing Forestry University*, 2011, 33(1):125-128.
- [34] Mu J, Yu Z M, Liu J J. Carbonized products of disused wood-based panels. *Journal of Beijing Forestry University*, 2009, 61(3):213-215.
- [35] Chen S H, Feng Y S, Mu J, et al. Bacteriostatic characteristics of disused wood-based board pyrolysis condensate liquid. *Journal of Beijing Forestry University*, 2012, 34(6):131-136.