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# Characteristics of thermal decomposition of bamboo with different chemical additives

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**Abstract** By means of the analysis of TG-DSC curves, we studied the effect of temperature and several additives, i.e., H<sub>2</sub>SO<sub>4</sub>, HCl, NaOH, H<sub>2</sub>O<sub>2</sub> and H<sub>3</sub>PO<sub>4</sub> on the performance of the thermal decomposition of bamboo. The results indicated that the weightlessness of pure bamboo powder may be divided into three stages, up to 700°C. At each stage, the effect of each chemical additive on the weightlessness rate of bamboo was different. In the end, we analyzed the function of additives in practical applications of the thermal decomposition of bamboo.

**Keywords** bamboo, thermal decomposition, TG-DSC curve, additive

## 1 Introduction

With the accelerating depletion of fossil fuel resources, which gradually leads to a deterioration of the environment, the development of renewable biological energy sources has become a new trend in the modern world. The use of forests as a biological resource has a unique position and role to play. Bamboo, commonly known as “the second forest”, is a very important part of forest resources. With the increasing use of bamboo in the processing industry, the amount of bamboo residue also increases. Development and utilization of bamboo resources are effective ways to ease the contradictions between timber supply and demand. It is very important to process these enormous renewable energy resources intensively. In this experiment, we have investigated the thermal decomposition of bamboo and reduced its conditions to those approaches for which technical and theoretical information is available to aid in the development and efficient use of bamboo (Xu et al., 2003; Fu et al.,

2004). We have looked at thermal gravimetric analysis (TGA), differential scanning calorimetry (DSC), differential thermal analysis (DTA) and mechanical thermal analysis (MTA) methods which could be used in thermal analysis. The first two methods were used in our research.

## 2 Materials and methods

### 2.1 Experimental material

In the study, we collected bamboo powder from the residue of the Lin'an Baifu Bamboo Products Co. Ltd. The additives HCl, H<sub>3</sub>PO<sub>4</sub>, H<sub>2</sub>O<sub>2</sub> and H<sub>3</sub>PO<sub>4</sub> were purchased from the ShuangLin Chemical Pharmaceutical Factory in Hangzhou City, Zhejiang Province of China. NaOH was purchased from the Ningbo Chemical Pharmaceutical Factory. All chemicals were of analytical grade.

### 2.2 Equipment

The following equipment was used in our project: a synthetic thermal analyzer (Netzsch STA409PC, Germany), a blast electric oven (101-1 Model) and an electronic balance (AG285).

### 2.3 Methods

#### 2.3.1 Sample preparation

We took some residue from the processing of fresh bamboo and ground the residue in a mill into powder. We used some of the powder to dry in an electric blast oven at 75–85°C for one day. After cooling, we sealed the powder in a plastic bag for further use. At the next step, we prepared five disposable paper cups and accurately weighed and placed 2.5 g of bamboo powder in each of the five disposable paper cups. Finally, we poured equivalent amounts of HCl, H<sub>2</sub>SO<sub>4</sub>, H<sub>2</sub>O<sub>2</sub>, H<sub>3</sub>PO<sub>4</sub> and NaOH (about 6 mL) in sequence into the cups for uniform wetting and dried them for further use.

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### 2.3.2 Process of thermal decomposition

The thermal decomposition of bamboo was conducted in the integrated thermal analyzer and each sample was tested by TG/DSC (TG/DSC means thermal gravimetric/differential scanning calorimetry). Because each test would require a considerable amount of time, we only chose one kind of sample to repeat this test for better replication and a small error. Other tests also were conducted only once. Using the synthetic thermal analyzer, the samples all less than 10 mg were put into the standard ceramic crucible. At the start of our test, we set the temperature of the crucible at 20°C, the speed of the rate of heating at 20 K/min (K: thermodynamic temperature units) and the final temperature of thermal decomposition at 700°C in order to obtain different products of thermal decomposition.

## 3 Results and discussion

### 3.1 Characteristics of thermal decomposition of pure bamboo powder

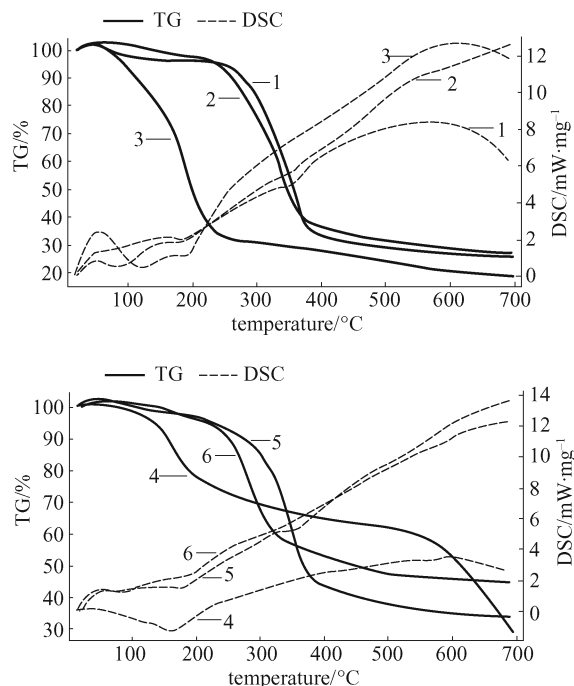
The process of thermal decomposition of bamboo includes a series of complex reactions, which may happen simultaneously or in succession. In fact, it is the thermal decomposition of three kinds of primary chemical components in the cell walls. In our experiment, the pure bamboo powder became weightless at 700°C (curve 1 in Fig. 1). This process can largely be divided into three stages.

1) When the temperature rose from 20°C at the start to about 260°C, the water that the bamboo had absorbed vaporized. Although the rate of weightlessness was not high in this process, the latent heat from vaporization of the adsorbed water and the total energy of hydrogen bonds were larger than usual. The reaction is as follows:

Bamboo  $\xrightarrow{\Delta}$  Bamboo which had lost water + H<sub>2</sub>O + Q (Q: the release of heat)

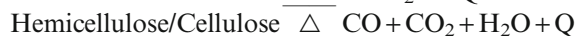
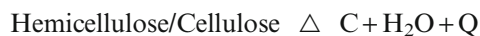
Most of the released water was free water with only a small amount of absorbed water.

2) At the start of the temperature range between 260 and 370°C, polymers, most of which consisted of hemicellulose, decomposed. Hydroxyl in the cellulose and hemicellulose was destroyed by heat, in which many hydrogen atoms were lost, only a few carbon atoms were lost and a large amount of water was released. Then, the hydroxyl and the combination of carbon-oxygen in the cellulose and hemicellulose were destroyed, which also can explain the phenomenon that the amounts of carbon, oxygen and hydrogen atoms decreased. At this stage, the rate of weightlessness was rather high and a polymerization reaction, a reverse reaction of thermal decomposition, occurred. The hemicellulose/cellulose

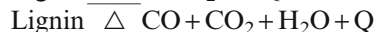


**Fig. 1** TG-DSC thermal decomposition curves of bamboo  
Notes: curve 1, pure bamboo powder; curve 2, treated with H<sub>2</sub>O<sub>2</sub>; curve 3, treated with H<sub>2</sub>SO<sub>4</sub>; curve 4, treated with H<sub>3</sub>PO<sub>4</sub>; curve 5, treated with HCL; curve 6, treated with NaOH.

decomposition has two forms. These processes are as follows:



3) Within the temperature range of 370 and 700°C, bamboo lost a small amount of weight from the decomposition of lignin and then the thermal decomposition tended to cease (Brown and Galwey, 1979; Jiang et al., 2005). The products of lignin decomposition were similar to those from the decomposition of hemicellulose. The reactions are as follows:



### 3.2 Mechanism of bamboo thermal decomposition

During the process of thermal decomposition of bamboo, the heat was first transferred to the granular surface of the bamboo powder and then to the interior of the granules. The process of thermal decomposition proceeded from the outside to the inside, layer by layer. The heated granules cracked into bamboo charcoal and volatiles, which consisted of condensed and uncondensed gas. The condensed gas turned into biological oil due to rapid condensation. The one-time pyrolysis produced biological charcoal, one-time biological oil and uncondensed gas. The volatiles in the granules further cracked into uncondensed gas and the second oil, showing thermal stability. At the same time, when the volatiles escaped from the granules, they

traveled through the surrounding gas and cracked further, which is called two-time pyrolysis. The bamboo finally produced biological oil, uncondensed gas and bamboo charcoal by thermal decomposition (Ma et al., 2005).

### 3.3 Comparison of characteristics of thermal decomposition with different additives

From Table 1, we must come to the conclusion that the different additives ( $H_2O_2$ ,  $H_2SO_4$ ,  $H_3PO_4$ , HCL and NaOH) clearly affected the thermal decomposition of bamboo powder. The table indicates that the additives affected not only the process of thermal decomposition or degradation of bamboo, but also the polymerization reaction of products of thermal decomposition and the loss rate of its final quality.

From Tables 1 and 2, we concluded that the different additives ( $H_2O_2$ ,  $H_2SO_4$ ,  $H_3PO_4$ , HCl and NaOH) affected the thermal decomposition of bamboo at each of the three stages at the same time. The additives also affected the final quality loss rate to a certain extent, especially the  $H_2SO_4$  (minimum) and NaOH (maximum). At the first stage the weightlessness rate of pure bamboo powder increased in the following order of absorption, application, increasing weightlessness: HCl,  $H_2O_2$ , NaOH,  $H_3PO_4$  and  $H_2SO_4$ , which indicated that all of the additives forced the weightlessness rate of bamboo to increase and accelerate the thermal decomposition. At the third stage, the weightlessness rate of the bamboo powder decreased in the following order application:  $H_2O_2$ , HCl, NaOH,  $H_3PO_4$  and  $H_2SO_4$ . In every group of handled material, the weightlessness rate went down. It is clear that the additives forced the weightlessness rate of bamboo down at the second stage. At the third stage, only the additive  $H_3PO_4$  clearly caused the bamboo powder to lose weight. The additives  $H_2O_2$ , HCl and NaOH caused the bamboo to lose weight largely at the second stage. The additive  $H_3PO_4$  caused the bamboo to lose weight mainly at the first and third stage. The DSC curves indicated that

several kinds of additives affected the heat absorption and release of the bamboo powder. The  $H_2SO_4$  additive caused the bamboo to produce an obvious exothermic peak at the first stage.

Because the  $H_3PO_4$  additive forced the weightlessness rate of bamboo to become much lower between 260 and 370°C, we concluded that phosphoric acid dehydrated and polymerized into polymerization phosphoric acid and partial polymerization phosphoric acid which covered the surface of bamboo after melting, so that the bamboo quickly dehydrated and charred into a film. At the same time, the coefficient of heat conduction of charcoal was lower than that of bamboo, which restrained heat transfer and played a role in retarding its burning. In addition, the thermal decomposition needed very high precision, so that the final temperature of thermal decomposition, the velocity of the rise in temperature, the size of granules of the bamboo powder and the time of detained reaction all had a certain effect on the results.

Given these results, we concluded that, for practical purposes, the effect of the several kinds of additives used in our thermal decomposition of bamboo, i.e., their spread to different kinds of biological material, the  $H_2SO_4$  additive forced the thermal decomposition of bamboo to accelerate before reaching 260°C and resulted in a lower quality loss of the bamboo before the temperature reached 700°C. We recommend using it in thermal decomposition and as a catalyst of liquefaction. After adding  $H_2SO_4$ , the amount of biological products from thermal decomposition of bamboo increased and the solid products were reduced, so that we could apply it to produce fuel gas. Between 260 and 370°C,  $H_3PO_4$  took effect by restraining the decomposition of cellulose and hemicellulose, so it can be used as a flame retardant and for heat insulation. Moreover,  $H_3PO_4$  can increase the rate of production of charcoal from bamboo, so that it can be used in producing charcoal and increase its output. From its DSC curve, it is seen that the HCL additive clearly forced the bamboo to absorb and release heat, so that it can be used in the thermal decomposition and

**Table 1** Thermal decomposition of bamboo with different chemical additives in a nitrogen atmosphere

additives	first stage (room temperature to 260°C)	second stage (260–370°C)	third stage (370–700°C)
pure bamboo powder	losing weight slightly, absorbing and releasing heat little.	losing weight quickly, releasing heat smoothly.	losing weight slowly, releasing heat firstly, and then absorbing heat.
$H_2O_2$	losing weight slightly, releasing heat slowly. There was a small endothermic peak around 200°C	losing weight quickly, releasing heat smoothly	losing weight slowly, releasing heat smoothly.
$H_2SO_4$	losing weight quickly. There was an endothermic peak around 50°C.	losing weight slowly, releasing heat smoothly.	losing weight slowly, releasing heat smoothly, absorbing little over 600°C.
$H_3PO_4$	losing weight quickly. There was a small endothermic peak around 170°C.	losing weight slowly, releasing heat slowly.	firstly losing weight slowly and then quickly, releasing heat slowly (after that absorbing heat little).
HCl	losing weight slightly, releasing heat slowly.	losing weight quickly, releasing heat smoothly.	losing weight slightly, releasing heat smoothly.
NaOH	losing weight slightly, releasing heat slowly.	losing weight quickly, over 300°C losing weight slowly, releasing heat smoothly.	losing weight slightly, releasing heat smoothly.

**Table 2** Weightlessness rate of bamboo at each stage (unit: %)

	pure bamboo powder	H <sub>2</sub> O <sub>2</sub>	H <sub>2</sub> SO <sub>4</sub>	H <sub>3</sub> PO <sub>4</sub>	HCl	NaOH
first stage	6	10	69	28	8	12
second stage	58	52	3	6	42	34
third stage	10	10	10	36	16	10
remnant	26	28	18	30	34	44

liquefaction of bamboo as a catalyst. After adding H<sub>2</sub>O<sub>2</sub>, the characteristics of thermal decomposition of bamboo powder were similar to those of pure bamboo powder. Therefore, H<sub>2</sub>O<sub>2</sub> is of little practical use in the thermal decomposition of bamboo.

#### 4 Conclusions

By analyzing our experimental results of thermal decomposition of bamboo powder, using different additives, we arrived at the following conclusions:

The weightlessness of pure bamboo powder can largely be divided into three stages before reaching 700°C: between 20 and 260°C; between 260 and 370°C and between 370 and 700°C.

The additives H<sub>2</sub>O<sub>2</sub>, HCl and NaOH forced the bamboo to lose weight mainly at the second stage, while the H<sub>2</sub>SO<sub>4</sub> caused the bamboo to lose weight mainly at the first stage. H<sub>3</sub>PO<sub>4</sub> made the bamboo lose weight both on the first and third stage. Its DSC curve indicated that only the H<sub>2</sub>SO<sub>4</sub> additive forced the bamboo to produce a clear

exothermic peak. This exothermic mechanism needs further investigation.

Through analyzing the effect of the three stages of thermal decomposition of bamboo with different additives, the additives not only affected the process of the decomposition of bamboo powder but also affected the polymerization reaction of the thermal decomposition products and the rate of final quality loss.

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