

## Pyrolysis and Combustion Characteristics of Boric Acid and Borax Treated Decorative Bamboo Filaments

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A cone calorimeter and thermogravimetric analysis were used in this work to determine the combustion and pyrolysis characteristics of decorative bamboo filaments before and after being treated with boric acid and borax (1:1) flame-retardants. The kinetics were calculated using the Coates-Redfern model. The results showed that in comparison to the control sample, the flame combustion time decreased from 52 s to 40 s, and the peak value of the heat release rate (PK<sub>HRR</sub>) and total heat release (THR) of the boric acid and borax treated samples were significantly decreased, by 21.0% and 22.2%, respectively. The peak value of the smoke release rate (PK<sub>SPR</sub>), total smoke production (TSP), and the specific extinction area (ASEA) were reduced substantially, by 90.6%, 93.3%, and 93.0%, respectively. After the boric acid and borax (1 to 1 ratio) flame retardant treatment, the pyrolysis range, the mass loss, the maximum mass loss rate, and the corresponding peak temperature of the samples all significantly decreased with the same heating rate. The activation energy of the BB-treated samples was higher than the control group, which indicated the boric acid and borax flame retardant had flame retardant efficiency.

*Keywords:* Decorative bamboo filament; Boric acid; Borax; Pyrolysis; Combustion; Kinetics

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### INTRODUCTION

Bamboo is an environmentally friendly material that is strongly advocated due to its fast material formation, high output, good material quality, and high economic efficiency (Li *et al.* 2018a). It has been widely used in many fields and is a major material used for decorative purposes. Decorative bamboo filaments are increasingly used in the fields of furniture production and interior decoration (Yu *et al.* 2015; Li *et al.* 2016; Zhao *et al.* 2019). As the need for environmental protection and low-carbon materials has increased, the interest in the development of decorative bamboo filament has also increased. However, bamboo filaments have a small cross section and contain a lot of extracts and hemicellulose, which are highly flammable and susceptible to strong heat radiation. Therefore, decorative bamboo filaments must be effectively flame retarded before they are able to be used as a raw material.

Flame retardants commonly used for wood or bamboo include boron, aluminum, nitrogen, phosphorus, antimony, sulfur, fluorine, chlorine, and bromine (Cui *et al.* 2016; Li *et al.* 2017; Wang *et al.* 2017). However, halogen acid released by the burning of halogen-containing flame retardants corrodes circuit system switches and other metals. In

addition, these toxic gases pose serious hazards to the human respiratory tract and other organs (Chen *et al.* 2009). Due to concerns about human health and environmental protection, halogen-containing flame retardants have been banned or reduced gradually in many countries. The research and application of phosphorus-nitrogen flame retardants in wood or bamboo is very extensive. (Liu 2013; Li *et al.* 2018b; Pan *et al.* 2018; Zhang *et al.* 2018). However, most phosphorus-based flame retardants contain small molecule phosphates, which have a low heat resistance, hydrolysis resistance, and flame retardancy with a risk of explosion. These disadvantages limit widespread its applications (Yu *et al.* 2017a). Furthermore, the traditional phosphorus-nitrogen and halogen flame retardants release toxic gases, smoke, and corrosive substances to different extents the during combustion process.

Due to their positive characteristics, *i.e.*, low smoke, low toxicity, antibacterial properties, and smoke suppressing properties, boron flame retardants have gradually attracted attention (Kurt *et al.* 2012; Yang *et al.* 2014). Boron-based flame retardants have been extensively studied in terms of its flame retardancy and anti-corrosive properties of wood materials. However, their application in the modification of bamboo decorative materials needs to be examined. Based on previous studies (Yu *et al.* 2017b; Li *et al.* 2018c), this study analyzed changes in kinetic properties of optimal decorative bamboo filaments in terms of their combustion performance, thermal degradation with different heating rates *via* cone calorimetry, and thermogravimetric analysis.

## EXPERIMENTAL

### Materials

#### *Sample and treatment*

The 4-year-old Moso bamboo samples (*Phyllostachys edulis* (Carr.) J. Houz) were taken from Anji, Zhejiang Province, China. After being air-dried, the moisture content was 9% to 10%, the diameter at breast height was approximately 100 mm to 110 mm, and the wall thickness was 12 mm to 14 mm. The size of the sample was 100 mm (tangential) × 100 mm (longitudinal) × 2 mm (radial), and width of a single bamboo filament was 3 mm. Ten samples with similar weights were selected to immerse in the boric acid and borax flame retardant treatment, which had a mass fraction of 20%, and boric acid and borax ratio of 1 to 1 at 60 °C. The filaments were immersed into boric acid and borax solution at 60 °C for 2 h. The samples were removed from the solution to drain the water, and then immersed in the solution at 60 °C for 2 h again. Finally, the bamboo filaments were placed into a humidity chamber at a constant temperature of 40 °C and a relative humidity (RH) of 60% to reach a constant mass.

### Methods

#### *Combustion performance via cone calorimetry*

The combustion performance of the samples with the boric acid and borax flame retardant treatment were tested by a cone calorimeter (FTT0242, Fire Testing Technology Co. Ltd., West Sussex, UK) according to ISO standard 5660-1 (2002). The dimensions of the samples were 100 mm × 100 mm × 2 mm, and they were placed horizontally under a cone calorimeter with a heat flux of 50 KW/m<sup>2</sup> during testing. A stainless steel cover with an opening of 0.0088 m<sup>2</sup> on the upper part was attached. The data was recorded by a computer every five seconds, with a test time of 110 s. Three samples were selected from

the control (CB) and the boric acid and borax (BB) treatment group, respectively. The main comparative parameters included the heat release rate, total heat release, smoke release rate, and total smoke release.

### Pyrolysis characteristics

The pyrolysis characteristics were tested with a thermogravimetric analyzer (TGA) (Q50, TA, Instruments, New Castle, DE, USA) under a nitrogen atmosphere (40 mL/min). The specifications for the bamboo powder was 60 mesh, and approximately 5 mg to 8 mg was analyzed for each testing. The samples were heated from room temperature to 1073 K at a heating rate of 10 K/min, 15 K/min, 20 K/min, and 25 K/min, respectively. The thermogravimetric (TG) and differential thermogravimetric (DTG) curves were obtained using Origin 8.0 software (Originlab Corporation, Northampton, MA, USA).

### Kinetic model

For bamboo-based fiber composites, the degradation reaction can be simply written as solid-solid gas (Wang *et al.* 2013; Chen *et al.* 2015). Referring to the isothermal chemical treatment, the reaction rate in the isothermal solid reaction can be expressed as Eq. 1,

$$\frac{d(\alpha)}{dt} = Kf(\alpha) \quad (1)$$

where  $\alpha$  is the conversion rate of biomass and can be calculated as  $\alpha = (w_0 - w) / (w_0 - w_\infty)$ ,  $t$  is the reaction time,  $f(\alpha)$  is the reaction mechanism function defined as  $f(\alpha) = (1 - \alpha)^n$  and  $K$  is the rate constant, a function depending on the actual reaction mechanism. Generally, these two parameters are related to the degree of degradation. The reaction rate constant  $K$  can be expressed as Eq. 2,

$$K = A \times \exp\left(-\frac{E_a}{RT}\right) \quad (2)$$

where  $A$  is the pre-exponential factor ( $\text{min}^{-1}$ ),  $E_a$  is the apparent activation energy (kJ/mol),  $R$  is the gas constant ( $8.314 \times 10^{-3}$  KJ/(mol·K)), and  $T$  is the heating temperature (K). During the experiment, the heating rate was a constant, which can be expressed as Eq. 3,

$$\beta = \frac{dT}{dt} \quad (3)$$

Combining Eq. 1, Eq. 2, and Eq. 3 yields Eq. 4,

$$\frac{d(\alpha)}{dT} = \frac{A}{\beta} \times \exp\left(-\frac{E_a}{RT}\right) \times (1 - \alpha)^n \quad (4)$$

Equation 4 is the fundamental expressions of the analytical methods to calculate the kinetic parameters on the basis of the TGA data.

During this research, the activation energies of the flame-retardant and control samples were calculated *via* a modified Coats-Redfern method.

Since the combustion of the biomass material belongs to a first order reaction, the reaction series  $n = 1$ . After separating variables and integrating Eq. 4, the corresponding equation was shown as below (Guo and Liao 2015), as Eq. 5.

$$\ln \left[ \frac{-\ln(1-\alpha)}{T^2} \right] = \ln \left[ \frac{AR}{\beta E_a} \left( 1 - \frac{2RT}{E_a} \right) \right] - \frac{E_a}{RT} \quad (5)$$

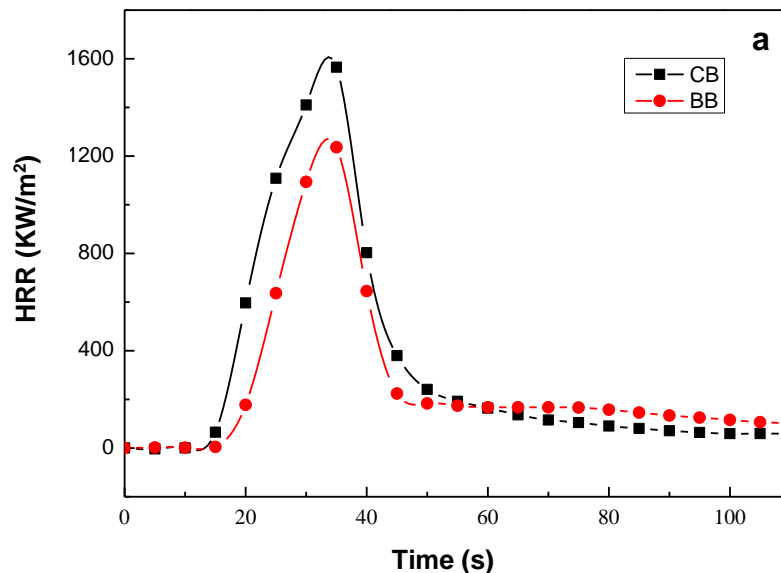
When  $\ln \left( \frac{-\ln(1-\alpha)}{T^2} \right)$  versus  $1/T$  is plotted, the slope is  $-E_a/R$ . The intercept was

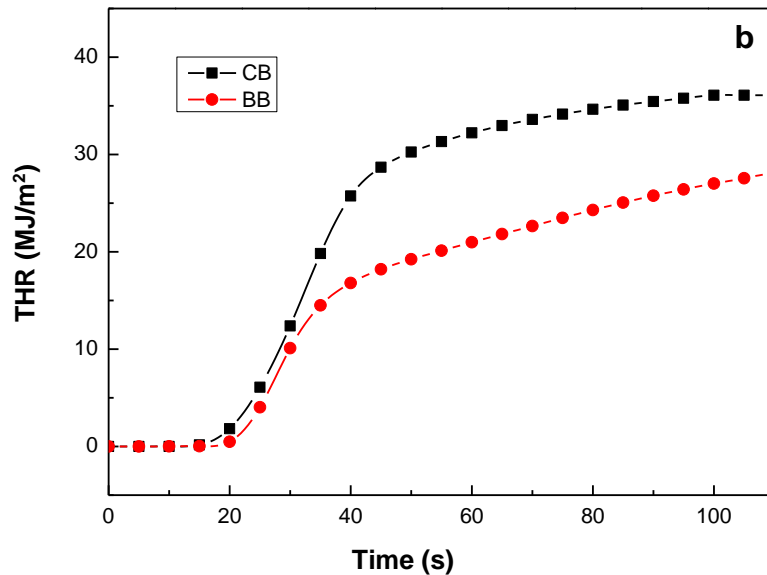
$\ln \left[ \frac{AR}{\beta E_{\alpha}} \left( 1 - \frac{2RT}{E_{\alpha}} \right) \right]$  but, by assuming that  $2RT \lll E_{\alpha}$ , the intercept can be arranged as  $\ln \left( \frac{AR}{\beta E_{\alpha}} \right)$ , where  $A$  can be calculated (Damartzis *et al.* 2011).

## RESULTS AND DISCUSSION

### Heat Release Analysis

Heat release is an important index for evaluating the combustion process. This quantity is usually characterized by the heat release rate (HRR) and the total heat release rate (THR). The HRR refers to the rate of heat release per unit area of the sample, and its peak HRR (pkHRR) is the maximum heat release rate. The THR refers to the total amount of heat released by the material per unit area in the whole combustion process. The HRR and THR values, which are proportional to the flame propagation rate and degree of fire hazard, respectively, are shown in Fig. 1 (Jin *et al.* 2017). The values of the corresponding parameters are listed in Table 1.





**Fig. 1.** Graphs of the heat release with time for the CB and BB-treated specimens: (a) Heat release rate (HRR) curves, and (b) total amount of heat release (THR) curves

**Table 1.** Heat Release and Appearance Time of Control Versus Treatment

Sample	Peak <sub>HRR</sub> ( KW/m <sup>2</sup> )	Time to Peak (s)	THR T110 ( MJ/m <sup>2</sup> )	Ignite Time (s)	Flameout Time (s)
CB	1565 (2.11)	35 (1.25)	36 (1.85)	11 (1.86)	63 (1.37)
BB-treated	1236 (2.52)	35 (1.17)	28 (1.53)	14 (1.54)	54 (1.24)

Note: The data values shown in the table are the average of each parameters. The standard deviation (SD) is shown in parentheses

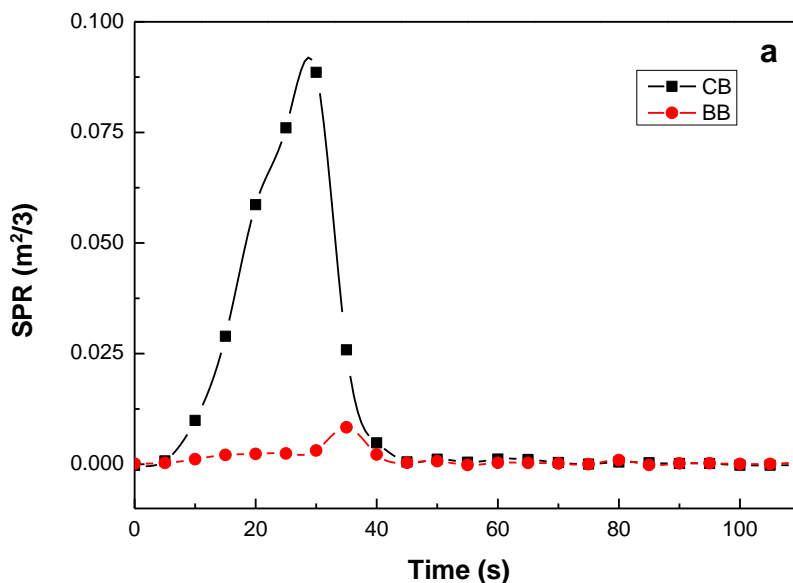
According to Fig. 1a, the peak value of the CB appeared at 35 s, and the peak value of the BB-treated samples also appeared at 35 s. There was a major difference in the peak heat release rate between the CB and BB-treated group. The values were 1565 kW/m<sup>2</sup> and 1236 kW/m<sup>2</sup>, respectively. The THR for the two groups are shown in Fig. 1b. The THR rapidly increased after ignition, and then it slowly increased, which indicated that flame combustion was the main exothermic stage and the inhibition effect of the flame retardant on combustion release also primarily occurred during this stage (Yang *et al.* 2014). The THR value of the BB-treated group was drastically lower than CB, which was reduced by 22.2% in 110 s. The slope of the THR curves started to increase after 20 s and decreased after approximately 40 s, and the maximum value corresponded to the PK<sub>HRR</sub>. As shown in Table 1, the ignition time for the control specimen was a little earlier than the HRR peak of the BB-treated group (11 s and 14 s, respectively). Meanwhile, the flameout time of the CB group was 9 s later than the BB-treated group. This indicated that the boric acid and borax flame-retardant could greatly reduce the flame combustion interval.

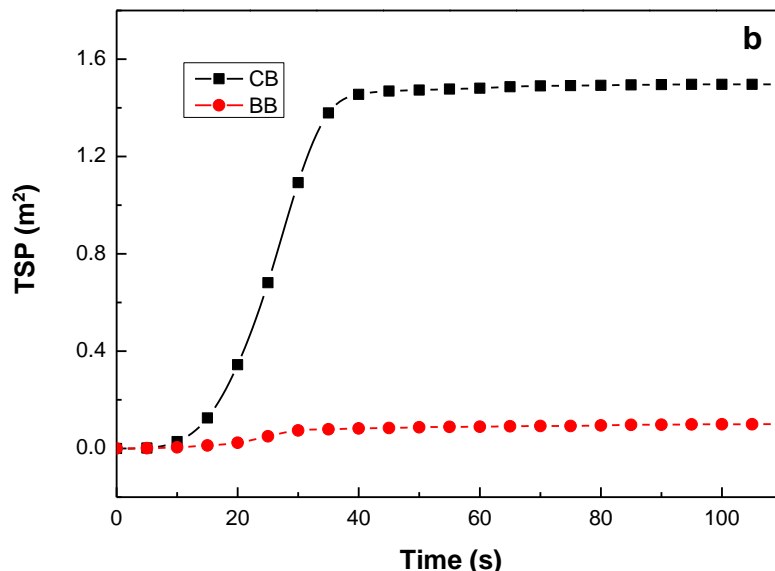
All the results suggested that the boric acid and borax flame-retardant could be used on decorative bamboo filament, as it was able to reduce the amount of heat release.

## Smoke Release Analysis

According to statistics, more than 85% of the deaths in a fire disaster are due to the smoke release (Jin *et al.* 2017). The smoke release rate (SPR) and total smoke release per unit (TSP) were seen as critical parameters in fire retardant performance evaluation. The SPR and TSP curves of the specimens before and after treatment and correlation parameters are shown in Fig. 2 and Table 2, respectively. In Fig. 2, the SPR and TSP curves for the BB-treated sample were drastically lower than those for the untreated bamboo filaments. Furthermore, the SPR and TSP curves remained nearly constant after 40 s, which meant that the flame combustion process of the samples had finished. As shown in Table 2, the values of  $pk_{SPR}$ , TSP, and ASEA were reduced by 90.6%, 93.3%, and 93.0%, respectively. In addition, the average production level of CO and CO<sub>2</sub> was decreased in varying degrees; the CO and the CO<sub>2</sub> were reduced by 21.01% and 37.64%, respectively. It could be seen from the parameters of smoke release (as shown in Table 2) that the boric acid and borax flame-retardant had excellent smoke suppression performance.

The excellent smoke suppression could be attributed to the chemical properties of boric acid and borax, which inhibited the formation of the intermediate of levoglucosan and increased the amount of carbon residue during the cellulose pyrolysis (Hu *et al.* 2013; Zhang *et al.* 2015).





**Fig. 2.** Smoke release curves of the decorative bamboo filaments; (a) Smoke release rate (SPR) curves; and (b) Total smoke release (TSP) curves

**Table 2.** Smoke Release of Control and Treated Decorative Bamboo Filaments

Sample	ASEA ( $\text{m}^2 \cdot \text{kg}^{-1}$ )	Average CO Production ( $\text{kg} \cdot \text{kg}^{-1}$ )	Average CO <sub>2</sub> Production ( $\text{kg} \cdot \text{kg}^{-1}$ )	Peak <sub>SPR</sub> ( $\text{m}^2/\text{s}$ )	TSP T110 ( $\text{m}^2$ )
CB	167.75 (2.81)	0.1054 (0.03)	3.2284 (0.11)	0.0886 (0.01)	1.4967 (0.10)
BB-treated	11.82 (1.54)	0.0833 (0.02)	2.0133 (0.10)	0.0083 (0.01)	0.1008 (0.08)

Note: The data shown in the table are the averages of each parameter. The standard deviation (SD) is shown in parentheses

### Pyrolysis Characteristics

The thermogravimetric and derivative thermogravimetric (DTG) curves of the CB and BB-treated decorative bamboo filaments, at different heating rates (10, 15, 20, 25 K/min), are shown in Fig. 3. The values of the corresponding parameters are listed in Table 3. During the pyrolysis process of decorative bamboo filaments, there were three stages: water loss, hemicellulose pyrolysis, and cellulose and lignin pyrolysis, which were caused by the thermal decomposition of the chemical components of the cell walls. During the pyrolysis process, the pyrolysis of bamboo began at 373 K to 420 K. When the ambient temperature reached above 540 K, the thermal decomposition of bamboo increased drastically. At temperatures above 770 K, the thermal decomposition reaction of the bamboo had basically ended (Liu *et al.* 2016; Wang *et al.* 2018).

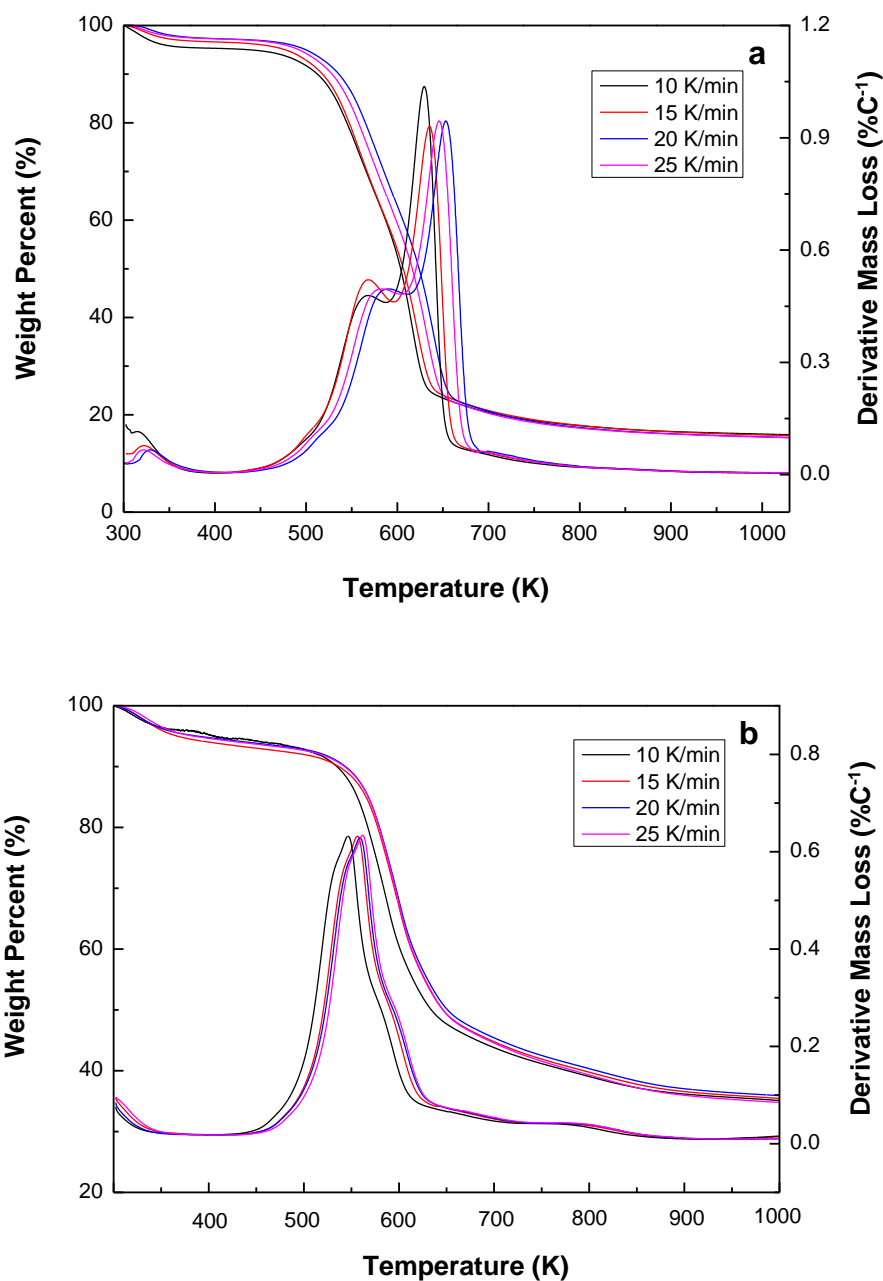
As shown in Fig. 3, the CB and BB had different slopes of mass loss reduction at the different heating rates, which indicated that the reaction rates of the samples varied at different heating rates. As shown in Fig. 3a, the mass loss of the CB was primarily caused by the decrease of moisture, which occurred at a temperature range of 330 K to 400 K. At

a temperature range of 450 K to 700 K, the derivative mass loss sharply increased, which was primarily caused by the decomposition of hemicelluloses, lignins, and celluloses. At temperatures greater than 700 K, the mass loss and derivative mass loss gradually slowed down, which was primarily due to the flameless combustion of carbon residue and the carbon residue forming a stable structure. As shown in the TG and DTG curves of the CB group (shown in Fig. 3a), the declining slope of the mass loss was incompatible at different heating rates, which indicated that the reaction rates of the samples varied at different heating rates (Liang *et al.* 2018).

Figure 3b showed that TG curve of the BB had a similar trend to the DTG curve at different heating rates, especially in the temperature range of 330 K to 370 K, for which the TG curve slowly decreased until the sample reached an oven-dry state. In contrast, the derivative mass loss was slightly higher than the CB mass loss, at a temperature range of 370 K to 470 K. This phenomenon should be attributed to the thermal decomposition of boric acid ( $\text{H}_3\text{BO}_3$ ). The thermal decomposition contained two stages, the first stage: the  $\text{H}_3\text{BO}_3$  dehydrated to form  $\text{HBO}_2$  at a temperature range of 370 K to 420 K, while the second stage (occurred at a temperature range of 420 K to 470 K) was when  $\text{HBO}_2$  converted to  $\text{B}_2\text{O}_3$ , which has a very high evaporation temperature. Meanwhile,  $\text{H}_3\text{BO}_3$  and the mannose residues (cis-diol structure) of the hemicelluloses reacted to form an acid complex, which promoted the dehydration, degradation, condensation, polymerization, and aromatization of the sample *via* the catalysis of proton acid (Wang *et al.* 2005). In addition, borax ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ) eventually generates  $\text{Na}_2\text{O}$  and  $\text{B}_2\text{O}_3$  during the pyrolysis process. At the temperature range of 470 K to 670 K, the high-temperature pyrolysis range of the BB-treated sample was shortened, which was due to the catalytic carbonization of the boric acid. Therefore, the ignition time of the BB was delayed, and the extinction time was lengthened during the combustion process, which corresponded to the data in Table 1.

The characteristic parameters of the three consecutive pyrolysis stages of the CB and BB-treated groups are listed in Table 3. According to the characteristic parameters of CB, the first stage was at a temperature range of 300 K to 423.2 K, 428.0 K, 431.3 K, and 434.1 K with a mass loss of 4.86%, 3.63%, 2.92%, and 3.02% (which corresponded to heating rates of 10 K/min, 15 K/min, 20 K/min, and 25 K/min, respectively). The mass loss of the CB in this stage was primarily caused by the decrease in moisture, which included free water, the physical adsorption of water, and crystal water (Wang *et al.* 2013; Chen *et al.* 2015; Dong *et al.* 2015).





**Fig. 3.** TG and DTG curves of the fire retardant treated decorative bamboo filaments at different heating rates; (a) TG/DTG curves of the CB group; (b) TG/DTG curves of the BB-treated group

The most dramatic reaction occurred during the second stage, at pyrolysis ranges of 423.2 K to 644.4 K, 428.0 K to 655.9 K, 431.3 K to 664.6 K, and 434.1 K to 674.3 K, respectively (in terms of the heating rates). The maximum mass loss rate was  $1.04\% \text{ } ^\circ\text{C}^{-1}$ ,  $0.927\% \text{ } ^\circ\text{C}^{-1}$ ,  $0.944\% \text{ } ^\circ\text{C}^{-1}$ , and  $0.943\% \text{ } ^\circ\text{C}^{-1}$  at 613.0 K, 618.3 K, 628.3 K, and 636.5 K, corresponding to heating rates of 10, 15, 20, and 25 K/min, respectively. During the third stage, the pyrolysis interval started at 644.4 K, 655.9 K, 664.6 K, and 674.3 K and ended at 1000 K with a mass loss of 7.6%, 7.5%, 7.35%, and 6.19%, respectively (in terms of the heating rates). As can be seen from the relevant data of the BB-treated samples (as shown

in Table 3), the pyrolysis process of the flame-retardant treated decorative bamboo filaments was also divided into three stages. In the first stage, the reaction temperature ranges were 300 K to 441.3 K, 445.2 K, 448.8 K, and 452.8 K with a mass loss of 5.9%, 6.88%, 6.13%, and 6.37% at the four rates above. In comparison, it was found that the mass loss of the BB-treated samples were slightly higher than that of the CB group, which was due to the pyrolysis of the boric acid and borax flame-retardant and the evaporation of the moisture in bamboo in this temperature range. The second stage is the main pyrolysis interval of the chemical components, which included cellulose, hemicellulose, lignins, and extracts, which occurred at a pyrolysis temperature range of 441.3 K to 638.7, 445.2 K to 651.5 K, 448.8 K to 660.0 K, and 452.8 K to 664.5 K with a mass loss of 49.9%, 49.0%, 49.2%, and 50.2%, corresponded to the four rates above. Furthermore, the maximum mass loss rate was  $0.632\% \text{ } ^\circ\text{C}^{-1}$ ,  $0.632\% \text{ } ^\circ\text{C}^{-1}$ ,  $0.630\% \text{ } ^\circ\text{C}^{-1}$ , and  $0.633\% \text{ } ^\circ\text{C}^{-1}$  at a temperature of 545.7 K, 556.4 K, 557.6 K, and 562.5 K at the four heating rates, respectively. Compared to the CB samples, the pyrolysis range, the mass loss, the maximum mass loss rate, and the corresponding peak temperature of BB-treated samples were drastically reduced. This phenomenon was attributed to the decomposition of the boron compounds, which could form a protective layer of glassy residues on the surface of BB-treated sample and accelerate carbonation (Yan *et al.* 2015; Cui and Yan 2018). During the third stage from 638.7 K to 1000 K, 651.5 K to 1000 K, 660.0 K to 1000 K, and 664.5 K to 1000 K (with respect to heating rates of 10 K/min, 15 K/min, 20 K/min, and 25 K/min), the mass loss was approximately 9.17%, 8.64%, 8.8%, and 8.63% in the slow pyrolysis stage. In this stage, the chemical components were carbonized to form loose porous materials, and some pyrolysis residues decomposed into ash gradually.

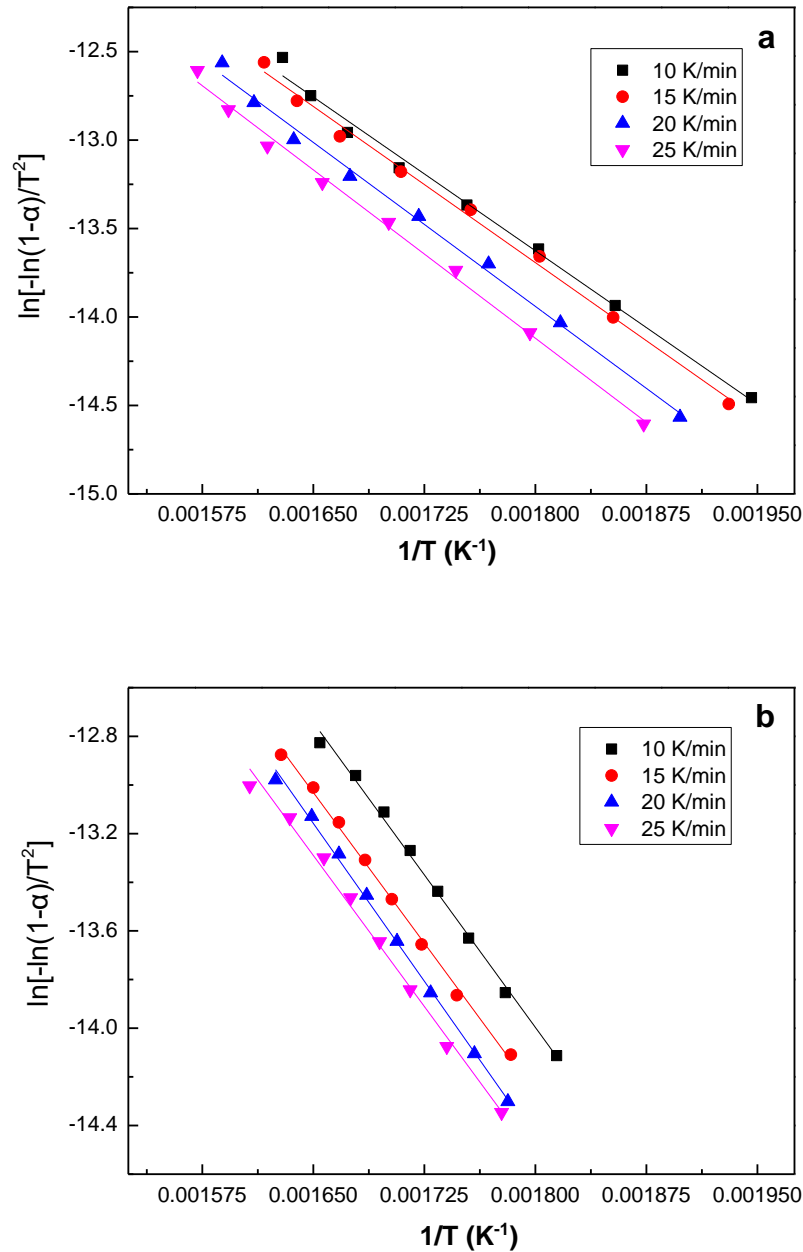
**Table 3.** Pyrolysis Characteristics of the CB and BB-treated Group

Sample		CB				BB			
$H_r$ (K/min)		10	15	20	25	10	15	20	25
The First Stage	$T_i$ (K)	300	300	300	300	300	300	300	300
	$T_e$ (K)	423.15	428.02	431.31	434.14	441.28	445.15	448.82	452.85
	MS (%)	4.86	3.63	2.92	3.02	5.9	6.88	6.13	6.37
The Second Stage	$T_i$ (K)	423.15	428.02	431.31	434.14	441.28	445.15	448.82	452.85
	$T_p$ (K)	613.03	618.31	628.3	636.48	545.66	556.41	557.61	562.48
	$R_{\max}$ ( $\% \text{ } ^\circ\text{C}^{-1}$ )	1.037	0.9273	0.9441	0.9433	0.6315	0.6319	0.6297	0.6332
	$T_e$ (K)	644.44	655.9	664.64	674.26	638.71	651.5	660.04	664.50
	MS (%)	71.5	73.03	74.25	75.37	49.93	49.03	49.16	50.21
The Third Stage	$T_i$ (K)	644.44	655.9	664.64	674.26	638.71	651.5	660.04	664.50
	$T_e$ (K)	1000	1000	1000	1000	1000	1000	1000	1000
	MS (%)	7.6	7.5	7.35	6.19	9.17	8.64	8.8	8.63

Note:  $H_r$  is the heating rate;  $T_i$  is the initial temperature;  $T_p$  is the peak temperature corresponding to maximum mass loss rate;  $R_{\max}$  is the maximum mass loss rate;  $T_e$  is the end temperature; and MS is the mass loss

### Kinetic Model

The Coats-Redfern method (Coats and Redfern 1964) is a model-based method that is derived from the Arrhenius equation. The apparent activation energy and frequency factor of samples were calculated by the linear fitting of the plot of  $\ln\left(\frac{-\ln(1-\alpha)}{T^2}\right)$  versus  $1/T$  under different heating rates. Figure 4 shows the relationship between  $\ln\left(\frac{-\ln(1-\alpha)}{T^2}\right)$  and  $1/T$  in the second stage; the average activation energy  $E_a$  and the number of phase relations  $R^2$  are shown in Table 4.



**Fig. 4.** The kinetic process of the samples using the Coats-Redfern model; (a) the CB group; and (b) the BB-treated group

According to Fig. 4, both the fitting lines of the CB group and the BB-treated group were approximately parallel, which indicated that having a different heating rate had little influence on the activation energy. Table 4 showed that the activation energy of the CB group at different heating rates was 48.2 kJ/mol, 48.9 kJ/mol, 49.4 kJ/mol, and 50.5 kJ/mol, respectively (corresponding to heating rates of 10 K/min, 15 K/min, 20 K/min, and 25 K/min). The activation energy of the BB-treated group was 70.4 kJ/mol, 70.8 kJ/mol, 71.2 kJ/mol, and 71.4 kJ/mol, (which corresponded to heating rates of 10 K/min, 15 K/min, 20 K/min, and 25 K/min, respectively), which were drastically higher than the activation energies of CB group. This indicated that the boric acid and borax flame retardant effect of the treated materials was obviously improved. In addition, the activation energy of the pyrolysis reaction slightly increased as the heating rate was increased. Furthermore, the correlation coefficients of the lines were all above 0.90, which indicated the Coats-Redfern model was feasible.

**Table 4.** Pyrolysis Kinetic Parameters of Coats-Redfern Method

	Heating Rate (K/min)	$E_a$ (KJ/mol)	Frequency Factor (A)	$R^2$
CB	10	48.15	2360.20	0.9930
	15	48.92	5297.60	0.9953
	20	49.41	11961.53	0.9959
	25	50.54	14513.37	0.9954
BB	10	70.37	287372.09	0.9871
	15	70.78	398467.80	0.9959
	20	71.16	675149.40	0.9915
	25	71.41	431127.36	0.9899

## CONCLUSIONS

1. During the combustion process, the flame combustion time decreased from 52 s to 40 s. In addition, the heat release rate (HRR) peak value and the total heat release (THR) of the BB-treated samples drastically decreased (21.0% and 22.2%, respectively) in comparison to the untreated decorative bamboo filaments.
2. The BB flame retardant has excellent smoke suppression properties. The peak value of the SPR, TSP, and ASEA were substantially reduced with the boric acid borax (BB) treatment and decreased by 90.6%, 93.3%, and 93.0%, respectively. The reduction of the average CO<sub>2</sub> production was slightly higher than the reduction of the average CO production. The CO production was reduced by 21.0% and the CO<sub>2</sub> production was reduced by 37.6%.
3. As the heating rate was increased, the temperature corresponding to the maximum mass loss rate increased and the differential thermogravimetric (DTG) curve shifted to a higher temperature. After the BB flame retardant treatment, the pyrolysis range, the mass loss, maximum mass loss rate, and corresponding peak temperature of the samples all were drastically reduced with the same heating rate.

4. The correlation coefficients of the pyrolysis kinetic parameters were all above 0.98, which indicated the Coats-Redfern model was feasible. The kinetic analysis showed that the activation energy of the BB was higher than the CB, which indicated that the BB flame retardant was efficient.

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