

Experimental Study on Emission Characteristics during Combustion of Single Bamboo Pellet

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Abstract. Some specific bamboo pellets were combusted in a tube furnace individually in different constant air flow rates (3,4 and 5 L/min) and at various temperatures (800, 900, 1000, 1100 and 1200 °C), in order to investigate the dynamic emission characteristics during various respective combustion processes. The results indicate that the increase of carbon monoxide(CO) amounts in 3 L/min air flow rate was caused by kinetic controlled combustion at 800 °C and by diffusion controlled combustion at 1100 and 1200 °C. The yield and concentration of nitric oxide(NO) reach the maximums at 900 °C, as well as the conversion rate from fuel-N to NO (9.17%). As combustion temperature increases, the yield and concentration of NO decline from the peak, and the conversion rate (from fuel-N to NO) falls to the lowest value (3.90%) at 1200 °C in 3 L/min air flow rate. When a bamboo pellet burns sufficiently almost none sulfur dioxide(SO₂) was released, while the S element can be kept in the ash or discharged in high-temperature flue gas in the form of sulfate which is converted from fuel-S. In oxy-lean atmosphere, SO₂ generates from the decomposition or oxidation of organic S during early devolatilisation, whereas more fuel-S probably are released in the forms of H₂S and CaS.

1 Introduction

With the depletion of conventional energy sources and the environmental damages by overuse of fossil fuels, biomass pellet fuel has been widely used in heating and power generation because of its extensive sources, renewable specific, CO₂ neutrality, and mature utilization ways to use, etc. [1]. However, the detrimental emissions of CO, NO and SO₂ during combustion cannot be ignored in large-scale application. Experts and scholars have carried out many thorough researches about biomass combustion and the accompanied emissions [2, 3]. At present, the researches on the characteristics of biomass pellets combustion are mainly focus on two aspects: one is based on the small sample of micro particles [4-8], avoiding the influence of internal heat and mass transfer in combustion process; the other is macro research based on pack-bed combustion [9-13], which focuses on the characteristics of flue gas emissions in the case of the coupling of chemical and physical factors during overall combustion. It is worth pointing out that the biomass pellet structure has a direct impact on the emission characteristics of combustion products [14, 15], and the internal heat and mass transfer processes also have important influences on the pyrolysis and combustion products [16].

In conclusion, the characteristics of single pellets in combustion cannot be completely presented in combustion tests of either fine particles or pack-bed pellets. In addition, the current investigation on flue gas emission characteristics during biomass pellet combustion mainly concentrates in the low temperature regions (≤ 1000 °C) [15, 16], while the generation rules at high temperatures are still lack of research. Based on the single bamboo pellet, the emission characteristics of harmful components in flue gas, such as CO, NO and SO₂, were studied under the conditions of different oxygen contents and temperatures, in order to provide references for the efficient and clean utilization of bamboo residues.

2 Materials and methods

2.1 Apparatus

Figure 1 shows the schematic diagram of the testing system for combustion experiments in this paper. The principle part is a temperature programming furnace reactor, with a horizontal tube of 60mm inner diameter and 300 mm effective heating length at the center. The furnace is heated by Si-Mo heating elements, allowing the highest operation temperature to reach up to 1550 °C. The tests were conducted in various air flow rates (3, 4 and 5 L/min) and temperatures (800, 900, 1000, 1100 and 1200 °C), respectively. A bamboo pellet carried by an alundum crucible was rapidly put into the center of the reactor with stable pre-set temperature and air flow rate. The flue gas produced by combustion of the bamboo pellet was sampled at the rear end of the reactor for a gas analyser typed VARIO plus Industry which recorded the concentrations of the uncondensable gas such as O₂, CO, NO and SO₂ every 2 s.

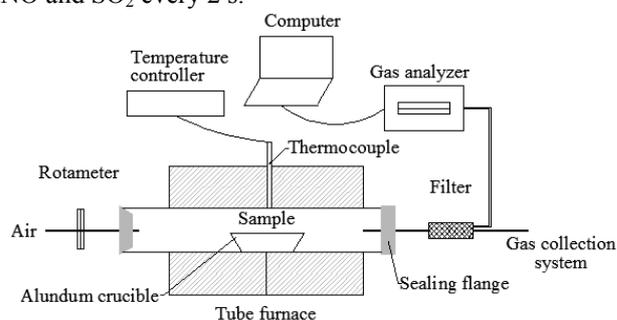


Figure 1 Schematic illustration of the reactor.

2.2 Materials

The raw materials including the residues of branches, leaves, sawdust, etc. was provided by a bamboo

processing mill located in Zhaoqing city, Guangdong province. The raw materials were crushed and extruded into densified pellets with diameters of approximately 8 mm and length of 40-60 mm. To ensure the representativeness, all samples were collected from one batch in dispersive spots. The compositions and element analysis results of the samples are listed in Table 1. The shape of the pellets under tests is shown in Figure 2, and the weight is around 1000 mg.



Figure 2 Bamboo pellet samples.

Table 1 Proximate and ultimate analysis of bamboo pellet.

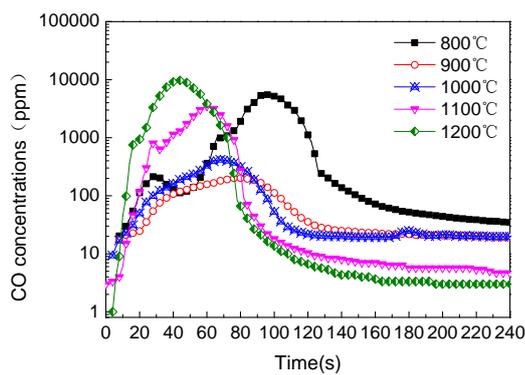
| Proximate analysis / % | | | | LHV _{ad} / MJ·kg ⁻¹ |
|------------------------|------------------|------------------|------------------|---|
| M _{ad} | V _{ad} | A _{ad} | FC _{ad} | |
| 9.73 | 69.09 | 4.65 | 16.53 | 16.12 |
| Ultimate analysis / % | | | | |
| C _{daf} | H _{daf} | O _{daf} | N _{daf} | S _{daf} |
| 41.04 | 5.99 | 37.49 | 1.01 | 0.09 |

2.3 Calculation methodology

The yields of CO, NO, SO₂ in flue gas were estimated by integration of the respective concentration curves as per Eq. (1):

$$N_i = \sum_{j=1}^k c_j \times 10^{-6} \times v_l / 60 \times 1000 \times t \times M_i / 22.4 \quad (1)$$

i : CO, NO, SO₂ v_l =3,4,5



(a)

where N_i is the total yield of one substance(mg), c_j is volume concentration at actual time(10^{-6}), v_l is the air flow rate(L/min), M_i is the molecular weight(g/mol), t is sampling time interval(s), k is the number of sampling points.

The conversion rates of fuel N and S were estimated by the emission amounts of NO and SO₂:

$$X_i = \frac{N_i \times A_r \times n / M_i}{m \times N_d} \times 100\% \quad i: N, S \quad (2)$$

where X_i is conversion rate(%), A_r is relative atomic weight, n is the number of a certain element in a gas molecule; m is the mass of fuel sample(mg), N_d is the mass fraction of a certain element in fuel(%).

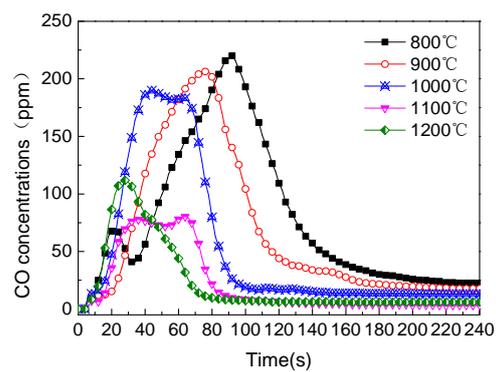
3 Results and discussion

3.1 CO emissions

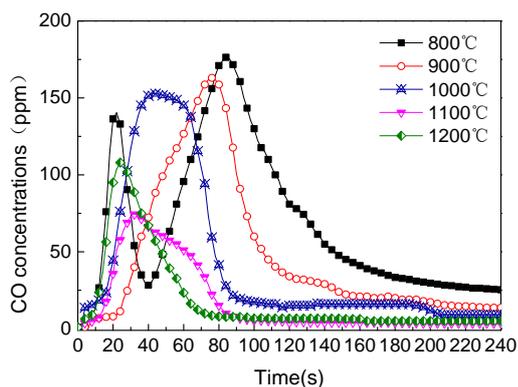
In Figure 3a~3d the variations of CO emission concentrations and yields are shown during bamboo pellet combustion under different temperatures and air flow rates. The CO concentration in flue gas directly reflects the actual combustion condition, and can be used to determine the interaction extent between volatile and other combustion products during pyrolysis and combustion.

Figure 3a~c show that the CO emission peaks narrow down with the increasing combustion temperature. It's because higher temperature leads to higher combustion rate, and hence the time required from the beginning of devolatilisation to the end of char combustion is shortened. For this reason, a bamboo pellet has better combustion characteristics at higher temperature.

Figure 3d shows that the yield of CO at 800 °C is much higher than other temperatures except 1200 °C. The

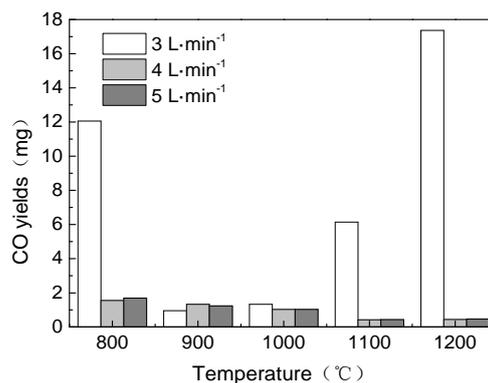


(b)



(c)

Figure 3 CO concentrations and yields at different combustion temperatures and air flows. CO concentrations in: (a) 3 L/min air flow, (b) 4 L/min air flow, (c) 5 L/min air flow. (d) CO yields at different combustion temperatures and air flows.



(d)

combustion may be in kinetic controlled at 800 °C, with higher devolatilisation rate than combustion rate, leading to a large amount of CO generation under the oxy-lean atmosphere. As the temperature rises, the combustion rate on the pellet surface exceeds the devolatilisation rate, and the combustion turns gradually into diffusion controlled in which the global combustion rate depends on the diffusion rate of oxygen from environment to particle surface. Therefore, to strengthen the combustion of bamboo pellet, sufficient oxygen supply capacity should be ensured in addition to combustion temperature increment.

During the combustion in 3 L/min air flow rate, the peaks of CO concentration curves at 1100 °C and 1200 °C are much higher than the peaks at 900 °C and 1000 °C, while it is contrary in 4, 5 L/min air flow rate. The former is due to the large instantaneous consumption of O₂ caused by the rapid devolatilisation at high temperature (as shown in Figure 4), so the emission concentrations and yields of CO increase significantly under oxy-lean atmosphere. Moreover, NO generates in larger amount at high temperatures, thereby to reduce more generating CO and decrease both of its concentration and yield.

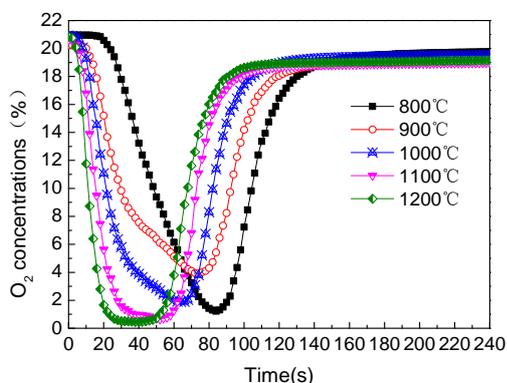


Figure 4 O₂ concentrations in 3 L/min air flow.

3.2 NO emissions

The highest temperature of the biomass pack-bed combustion is generally not more than 1300 °C [17] at

which NO emissions account for more than 90% of total NO_x and most of the NO consists of fuel-NO, the rest such as thermal-NO and prompt-NO can be ignored. Therefore, the characteristics of fuel-NO emission are analyzed emphatically in this paper. Under the test conditions of this paper, most of the fuel-N comes from volatile-N whereas seldom from char-N^[18]. Fuel-N mainly transfers to NO precursors (HCN, NH₃ and HNCO) in the form of volatile-N during combustion. The precursors can transfer to NO or N₂ in reduction or oxidation atmosphere respectively, whereas char-N is oxidized to NO primarily.

Figure 5a shows that in air flow rate of 3L /min, the NO concentration peaks in flue gas differ largely at various temperatures, e.g. the highest peak appears at 900 °C, the following lower peak at 1000 °C. During devolatilisation, the largest proportion of component in volatile-N is NH₃, while the slightly lesser one is HCN^[19]. However, NO productions are directly affected by the changes of NH₃ and HCN in the volatile with various combustion temperatures. The changing rules of NH₃ and HCN in volatile with combustion temperature variation are relevant to the NO production. Above 900 °C, the NH₃ formation rates are stable or abate slightly [20], and the concentrations of NO reach the maximum. Moreover, large amount of CO generate during combustion at 800 °C, 900 °C, and 1200 °C, forming oxy-lean atmosphere under which hardly can NH₃ and HCN transform to NO by reaction with O₂, additionally more NO are reduced to N₂.

Figure 5b and c show that the shapes of NO concentration curves at different temperatures in air flow rate of 4 and 5 L/min are similar, i.e. the characteristics of NO production and emission are stable at various temperatures in oxy-abundant atmosphere. Whereas in air flow rate of 3 L/min, NO concentration curves became complicate within the relative oxy-lean atmosphere. At relatively high temperatures (1100 and 1200 °C) and in oxy-lean atmosphere (3 L/min air flow rate), the bamboo pellet is burned incompletely to form large amounts of CO accompanying with hydrocarbon, e.g. CH₄ and SO₂. All of these intermediate products react with fuel-N intricately, making the generation mechanism of NO more complicated.

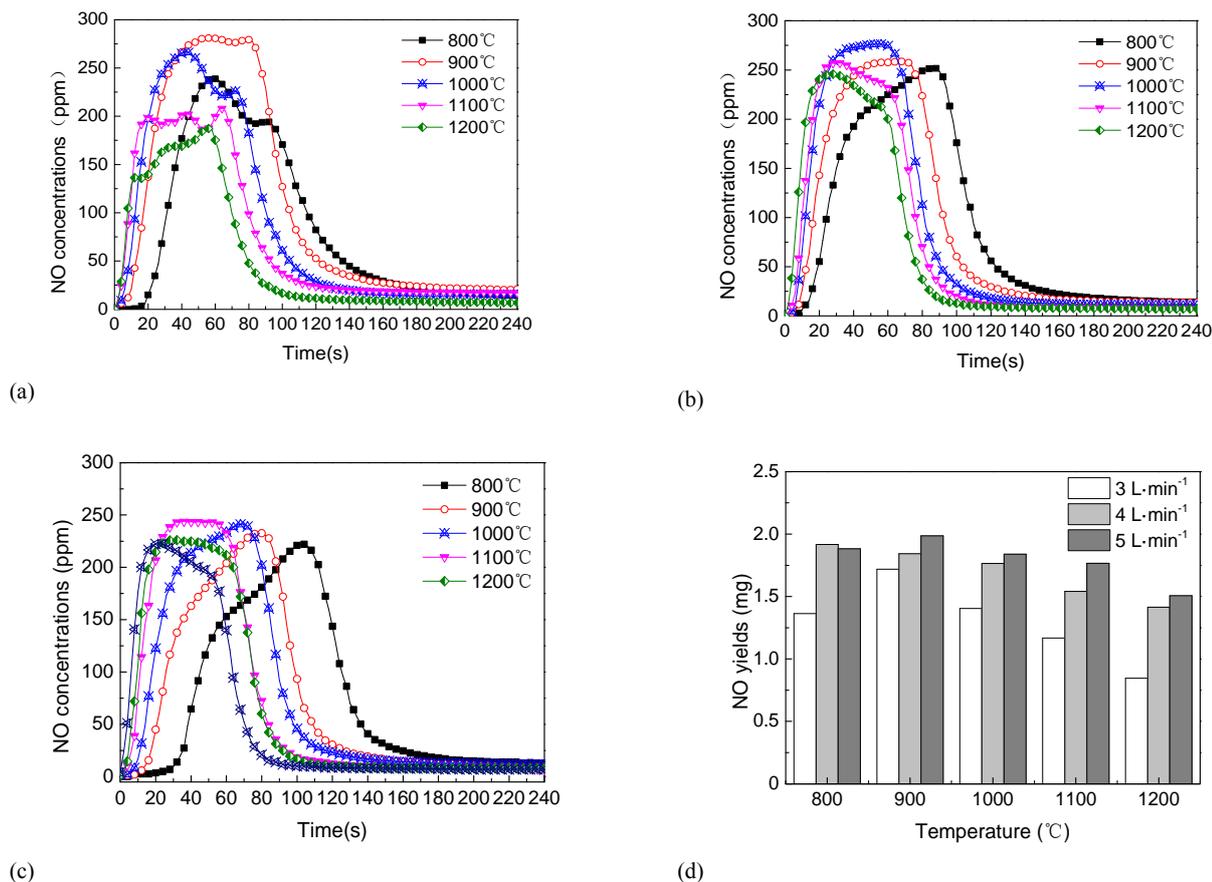


Figure 5 NO concentrations and yields at different combustion temperature and air flow. NO concentrations in: (a) 3 L/min air flow, (b) 4 L/min air flow, (c) 5 L/min air flow. (d) NO yields at different combustion temperatures and air flows.

Figure 5d shows the yield properties of NO in various atmospheres and at different temperatures. In oxy-abundant atmosphere, NO emission level reaches the maximum at 900 °C, consistent with Tian *et al.* [20]. Above 900 °C, the NO yields and fuel-N conversion rates can be reduced by decreasing the air supply (Table 2). Therefore, the NO yield during bamboo pellet combustion can be reduced effectively by burning in oxy-lean atmosphere.

Table 2 Fuel-N conversion rates at different combustion temperatures and air flows.

| Air flow/ L·min ⁻¹ | Conversion rate/ % | | | | |
|----------------------------------|--------------------|--------|---------|---------|---------|
| | 800 °C | 900 °C | 1000 °C | 1100 °C | 1200 °C |
| 3 | 6.30 | 7.93 | 6.48 | 5.39 | 3.90 |
| 4 | 8.85 | 8.51 | 8.15 | 7.12 | 6.53 |
| 5 | 8.70 | 9.17 | 8.49 | 8.15 | 6.96 |

3.3 SO₂ emissions

During bamboo pellet combustion, the S element is released in forms of H₂S and SO₂ in gas phase mostly. The sulfur compounds are mainly produced by the decomposition of organic S compounds with poor heat stability or inorganic sulfate in volatile combustion stage and char combustion stage respectively [21].

Figure 6 shows that SO₂ can only be detected in 3L /min air flow rate at 800, 1100 and 1200 °C. It can be concluded that sulfur compounds can be absorbed by the matrix of char [21] at relatively lower temperature and in oxy-abundant atmosphere during combustion, but the absorption capacity of char matrix will reduce at relatively higher temperature, leading to more SO₂ oxidized from element S released, which can subsequently react with alkali compounds to form stable inorganic sulfate (chemical formula (3)) in solid phase [22]. In Figure 3a~3c, we can find that nearly no SO₂ generates during sufficient burning.

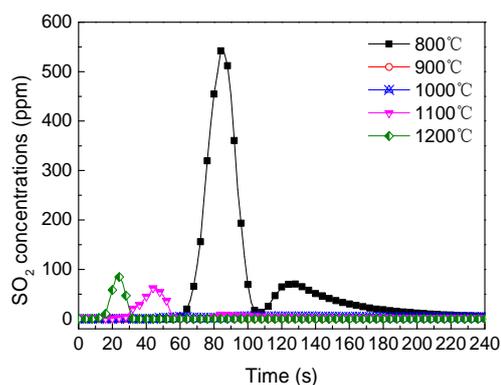
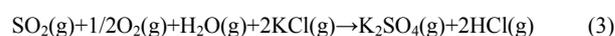
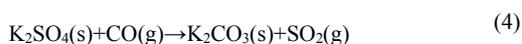


Figure 6 SO₂ concentrations in 3 L/min air.

As mentioned before, the combustion is in kinetic controlled under strong reduction atmosphere, thus in air flow rate of 3L /min and at combustion temperature of 800 °C, against the reaction according to formula (3) that SO₂ can release with flue gas, while the concentration curve is similar to CO under the same condition (Figure 3a). With the deepening of char combustion, the sulfates detained in the char matrix will decompose in strong reducing atmosphere (formula (4)) to release a small amount of SO₂, forming the second peak of SO₂ concentration curve(Figure 6). At 1100 and 1200 °C, SO₂ is released with flue gas, yet isn't converted into sulfate as the SO₂ will be difficult to react with alkali compounds (formula (3)) while the pellet is burnt in oxy-lean atmosphere(Figure 3a). The rest of the S-containing compounds in gas phase mainly are discharged in forms of H₂S and CaS^[15].



4 Conclusions

Combustion of an individual bamboo pellet is in chemical kinetic controlled at 800 °C that the rate of devolatilisation is much larger than pellet-surface combustion. The peaks of CO concentration curves narrow down as the combustion temperature increases in the air flow rate of 4 and 5 L/min, shortening the time from the beginning of devolatilisation to the end of char combustion.

Both the peaks of concentration and total yields of NO in flue gas reach their maximum values at 900 °C, and the conversion rate from fuel-N to NO is no more than 9.17%, i.e. the highest proportion recorded in tests. With increasing combustion temperature and enhancing reduction atmosphere, some of the released NO are reduced and the NO emission level is declined, while only 3.90 % of fuel-N is transferred into NO in air flow rate of 3 L/min at 1200 °C. The lowest conversion rate is recorded in tests.

Almost no SO₂ is released with flue gas in full combustion because the fuel-S is primarily transferred to sulfate detained in the ash. However, SO₂ can be detected in flue gas during incomplete combustion, which is mainly produced from decomposition and oxidation of organic S during devolatilisation, as only a small part from decomposition of inorganic S in char combustion stage. Additionally in reduction atmosphere, some of the element S release in the forms of H₂S and CaS.

Acknowledgments

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