Thermogravimetric analysis of the co-combustion of bituminous coal, rice straw and sewage sludge

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Abstract—At present, it is recognized as the most promising way to dispose biomass by mixed combustion with coal in thermal power plants. The thermal behavior of bituminous coal (BC), rice straw (RS), sewage sludge (SS) and their blending during combustion processes was investigated by thermogravimetric analysis (TGA) in this paper. RS and SS are blended with BC at the ratios of 10\%, 20\%, and 30\% respectively. The ignition performance, combustion characteristics and burnout performance of BC mixture were investigated and compared. RS improves the ignition performance and the comprehensive combustion index decreased with the increase of the RS blending ratio. SS decreases the flammability index and comprehensive combustion index of BC mixture, when the blending rates over 20\%, which makes difficult the ignition and combustion of the BC mixture.

1. Introduction

Biomass fuel has the characteristics of high moisture and volatile content but low calorific value, so the thermal economy of biomass combustion alone is not high. Mixture of bituminous coal (BC) and biomass can not only reduce the fuel cost of power plant, but also solve the problem of disposing solid wastes such as rice straw (RS) and sewage sludge (SS).

Li [1] studied the combustion characteristics of sludge with different proportions by thermogravimetric analysis (TGA). The study showed that in mixed combustion, with the increase of dry sludge proportion, the peak weight loss rate of volatile components of mixed samples increased, the peak time of weight loss rate appeared earlier, and the temperature at which it appeared decreased. Tang [2] showed that the increase of heating rate was conducive to the rapid treatment of sludge and utilization of heat energy, but the total weight loss rate was small and the reduction was poor. Niu [3] showed in their study on co-combustion characteristics of municipal SS and BC that with the increase of SS blending ratio and heating rate, the ignition and burnout indexes of the mixture were improved. Fu [4] showed that with the increase of oxygen concentration, the combustion rate of SS and coal mixture sample increased and the combustion became more intense. Rago [5] studied the synergistic effect of carbonized biomass-plastic waste and coal co-firing, and the study showed that the interaction of waste type and waste mixture in co-firing affected the synergistic effect of waste coke and coal...
co-firing.

The above summary of the literature indicates that the technology of biomass and BC as a blended fuel is currently still in the research phase. At present, most of the studies on the mixed combustion are aimed at the mixed combustion of coal or the mixed combustion between BC and a single biomass, but there are few studies on the simultaneous mixed combustion of BC and a variety of biomass. The aim of this work is to deal with RS, SS and BC, convert them into valuable energy and therefore find a potential solution for management. In the paper, the co-combustion characterization, interactions between RS, SS, BC and their mixture through TGA were studied and to determine the optimum operating conditions of the co-combustion processes.

2. Experiment samples and procedure

2.1. Experiment samples

The SS samples used in the experiment were dehydrated sludge from a sewage treatment plant north of China. The RS samples were collected from a farm in Hebei province. The BC samples were obtained from a coal mine in Shanxi province. The proximate analysis, ultimate analysis and net calorific value (NCV) of RS, SS and BC on dry basis were shown in Table 1. Compared with BC, the RS and SS has high volatile, moisture and oxygen, but low fixed carbon and sulphur. Their chemical properties and combustion characteristics will significantly vary. All samples were dried in oven at 105°C for 24 h, then pulverized and sieved to get uniform particle with a grain size of 75-96 µm. Due to the low NCV of biomass, the ash melting temperature of BC blended with biomass is reduced, would causing problems such as slagging, so that in the actual operation of the power plant, a high proportion of biomass will not be blend into BC. Therefore, the RS and SS are blended with coal at the mass percentages of 10%, 20% and 30% respectively [6].

Table 1 The proximate analysis, ultimate analysis and net calorific value of RS, SS and BC

| Samples | Moisture | Ash | Volatile | Fixed Carbon | C | H | O | N | S | net calorific value (kJ/kg) |
|---------|----------|-----|----------|--------------|---|---|---|---|---|----------------------------|
| BC      | 1.61     | 26.96 | 13.91    | 57.52        | 61.38 | 2.89 | 33.20 | 0.97 | 1.57 | 21248.80                   |
| RS      | 9.8      | 18.73 | 59.55    | 11.92        | 35.00 | 4.88 | 58.28 | 1.51 | 0.33 | 12678.07                   |
| SS      | 4.17     | 49.57 | 45.42    | 0.84         | 20.27 | 2.94 | 73.43 | 2.38 | 0.98 | 6579.35                    |

2.2. Experiment procedure

Hitachi TG/DTA7300 thermogravimetric and differential thermal integrated thermal analyzer was used in the experiment. About 10mg samples were put into a crucible with a gas flow rate of 100 mL/min and an atmosphere of air. The temperature range was from room temperature to 1000°C with a heating rate of 20°C/min. In order to ensure the accuracy of the experimental results, all the experiments were conducted twice and the reproducibility was satisfied.

3. Results and discussion

3.1. Derivation of parameters

TG-DTG method was adopted to determine the ignition temperature $T_i$ and the burnout temperature $T_h$. However, $T_i$ can only reflect the reaction ability at the initial combustion, but cannot summarize the whole combustion process. Therefore, it is necessary to comprehensively evaluate the ignition difficulty and combustion performance of each sample according to the flammability index $C$ and the integrated combustion index $S$.

Flammability index $C$ represents the chemical reaction activity at initial combustion. The larger the $C$, the better the combustion and ignition stability of fuel [7].

$$C = \left(\frac{dw}{dt}\right)_{max} / T_i^2$$  

(1)
Where \((\text{d}\omega/\text{d}t)_\text{max}\) is the burning rate corresponding to the weight loss ratio on the differential thermal gravity (DTG) curve. The ignition temperature \(T_i\) corresponds to the point at which the burning profile underwent a sudden rise. \(T_i\) of samples were determined from their burning profiles.

The integrated combustion index \(S\) can fully reflect the ignition and burnout performance of the fuel, the higher the \(S\), the better the overall combustion performance, which is defined as:

\[
S = (\frac{\text{d}\omega}{\text{d}t})_{\text{max}} (\frac{\text{d}\omega}{\text{d}t})_{\text{mean}} / T_i^2 T_h
\]

Where \((\text{d}\omega/\text{d}t)_{\text{mean}}\) is the average burning rate, the burnout temperature \(T_h\) is obtained when the mass loss accounts for 98% of the total quality loss[8].

3.2. Analysis of the results

3.2.1. Mono-combustion characteristics analysis

The TG and DTG curves of BC, RS and SS combustion as shown in Fig.1. According to TG curves, all samples have basically burned out when the temperature exceeds 800°C, and the total weight loss of RS is the largest, followed by BC and SS. This result is consistent with the proximate analysis results in Table 1. The DTG curve of BC shows that it has only one obvious peak of weight loss, while RS and SS have multiple peaks of weight loss.

![Fig.1 Mono-combustion TG and DTG curves of BC, RS and SS](image)

The volatile and fixed carbon of BC are burned almost simultaneously. Therefore, an obvious weight loss peak appears between 400°C and 650°C, and the corresponding peak temperature reaches 517°C. Due to the slow combustion rate of fixed carbon, the weight loss peak of BC is low and wide. In addition, the weight of BC increased slightly between 170°C and 345°C, which was mainly due to its physical and chemical adsorption on oxygen [9-11]. There are three weight loss peaks in the combustion process of RS and SS. The first peak is caused by water precipitation. The second one was appeared at 270°C and 320°C, respectively, which was the precipitation and combustion stage of volatile matter. The third one was appeared near 360°C and 740°C, respectively, which was the combustion stage of fixed carbon. Because the combustion rate of volatile matter is faster than that of fixed carbon in RS and SS, the second weight loss peak was higher the third one. The volatilized weight loss peak range of ES was close to that of fixed carbon, and their interaction was more obvious in the combustion process, while the volatilized weight loss peak range of SS was far from that of fixed carbon, and their interaction was weaker in the combustion process.

The combustion characteristic parameters for all the samples as shown in Table 2. The ignition temperature of RS and SS is lower than that of BC, and the burnout temperature of medicinal residue is the highest. The maximum burning rate and average burning rate of RS were the largest, while the burning rate of SS was lower than that of BC. The combustibility index and comprehensive combustion characteristic index of RS and SS were larger than those of BC, and the combustion characteristic parameters corresponding to RS were the largest.
3.2.2. BC-RS co-combustion characteristics analysis

In the mixture of BC-RS, the RS content of the blend ratio were set by mass as 10%, 20%, 30%, which were named as 90BC10RS, 80BC20RS, 70BC30RS, respectively. The TG and DTG of Co-combustion BC-RS were shown in Fig.2. The TG curve of the BC-RS mixture is between the TG curves of the BC and RS samples alone, with the increase of the RS blending ratio, the total weight loss of the mixture gradually increases due to the less ash content of the RS. The first weight loss peak appeared at about 300°C in the BC-RS mixture, the weight loss rate increases continuously as the RS blending ratio increases. The main reason is that the RS has high reactivity, and it burns first after the temperature rises, and the more the amount of blending, the faster the burning rate, leading to a gradual increase in the peak weight loss. The amount of RS blending has a great impact on the combustion of BC-RS mixture in the later stage of combustion. The peak of the second weight loss peak in the BC-RS combustion process is reduced, the peak width is narrowed, and there is a tendency to move to the low temperature zone. The precipitation and combustion of the volatile in the mixture improves the combustion of BC-RS in advance.

![Fig.2 Co-combustion TG and DTG curves of BC-RS](image)

The co-combustion characteristic parameters of BC-RS mixture as shown in Table 3. With the increase of the blending ratio of RS, the ignition temperature, burn-out temperature and maximum burning rate of the mixture decrease, and the average burning rate increases. However, neither the flammability index nor the comprehensive combustion index changes linearly with the blending ratio of straw. When the blending ratio of RS is increased to 30%, the flammability index and comprehensive combustion index of the mixture will be nearly 4 times that when the blending ratio of RS is 10%, which is because the volatile precipitation of RS content greatly improves the ignition performance and comprehensive combustion characteristics of the BC-RS mixture.

![Table 2](image)

| Samples     | $T_i$ (°C) | $T_{max}$ (°C) | $T_f$ (°C) | ($\frac{d\theta}{d\phi}$)$_{max}$ %/min | ($\frac{d\theta}{d\phi}$)$_{max}$ %/min | $C$ ($10^2$ min$^{-1}$°C$^{-1}$) | $S$ ($10^2$ min$^{-2}$°C$^{-2}$) |
|-------------|------------|---------------|------------|----------------------------------------|----------------------------------------|----------------------------------|----------------------------------|
| BC          | 462        | 517           | 640        | 11.12                                  | 1.5                                   | 5.21                             | 1.22                             |
| RS          | 260        | 274           | 601        | 58.83                                  | 1.69                                  | 87.03                            | 24.47                            |
| SS          | 205        | 320           | 759        | 4.36                                   | 1.06                                  | 10.37                            | 1.45                             |

3.2.3. BC-SS co-combustion characteristics analysis

In the mixture of BC-SS, the SS content of the blend ratio were set by mass as 10%, 20%, 30%, which were named as 90BC10SS, 80BC20SS, 70BC30SS, respectively. The TG and DTG of Co-combustion BC-SS were shown in Fig.3. The TG curve of the BC-SS mixture is between the TG...
curves of the BC and SS samples alone, with the increase of the SS blending ratio, the total weight loss of the mixture gradually decreases due to the more ash content of the SS. As SS blending ratio is 10%, the mixture has two weight loss peaks. The temperature range of the higher weight loss peak is close to that of BC combustion alone, indicating that the combustion of BC is the main component in this range, and the weight loss peak of moisture and volatile precipitation and combustion is not obvious. With the increase of the blending ratio of SS, the weight loss peak value of volatile matter gradually increases at about 300℃. The main weight loss peak of the mixture combustion is always close to that of BC combustion alone, the peak value decreases, and the peak width gradually narrows.

The co-combustion characteristic parameters of BC-SS mixture as shown in Table 4. As the blending ratio of SS increases, the ignition temperature of the BC-SS mixture decreases and the ignition is advanced, the burnout temperature rises, the time required for burnout is prolonged, and the average combustion rate decreases, which is not conducive to the stable combustion of the mixture. The flammability index and comprehensive combustion index decrease, the combustion characteristics of the BC-SS mixture become worse, and SS content over 20% is not conducive to the ignition and combustion of the mixture.

Table 4  Co-combustion characteristic indexes of BC-SS

| Samples | T_i (℃) | T_max (℃) | T_th (℃) | (dω/dθ)_max (%/min) | (dω/dθ)_θmax (%/min) | C (10^3min^-1°C^-1) | S (10^-7min^-2°C^-1) |
|---------|---------|-----------|----------|---------------------|----------------------|----------------------|----------------------|
| 90BC10SS | 487     | 549       | 668      | 10.73               | 1.44                 | 4.52                 | 0.98                 |
| 80BC20SS | 462     | 531       | 689      | 9.95                | 1.38                 | 4.66                 | 0.93                 |
| 70BC30SS | 455     | 546       | 706      | 7.68                | 1.35                 | 3.71                 | 0.71                 |

4. Conclusion

In this paper, Thermogravimetric analysis (TGA) method is adopted to study the thermal behavior of bituminous coal (BC), rice straw (RS), sewage sludge (SS) and their mixture. The main conclusions can be summarized as follows:

(1) The performance of BC and biomass in the combustion process is very different. There’s only one weightlessness peak on DTG curve, but three on RS and SS.

(2) RS improves dramatically the combustion characteristics of BC mixture, With the increase of the blending ratio of RS, the ignition temperature, burn-out temperature and maximum burning rate of the mixture decrease, and the average burning rate increases.

(3) With the increase of the blending ratio of SS, the flammability index and comprehensive combustion index of BC mixture decrease, and when the blending ratio exceeds 20%, which is not conducive to the ignition and combustion of the BC mixture.

These results provide a theoretical basis for the new technology of combined power generation of RS and SS energy recycling. In terms of the future work, Study blend RS and SS with BC in a reasonable ratio will be carry out to improve the combustion performance of BC and reduce power generation costs.

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