Orthogonal experiment analysis of coal gangue and corn straw mixed burning under considering multiple factors

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Abstract. Combustion test of multi-mass blending ratio of corn straw and coal gangue by using thermogravimetric analyzer with different heating rates and different oxygen concentrations. Comprehensive consideration of the synergy between factors and factors, combustion performance analysis of ignition performance, flammability, volatiles precipitation performance and comprehensive combustion performance. The results show that the optimum combination of ignition and combustibility in order of priority is: oxygen concentration 30%, mass blending ratio of corn straw and coal gangue 2:3, heating rate \( v = 10 \text{ K/min} \). The optimum combination of flammability and release of the volatile matter in order of priority is: oxygen concentration 30%, mass mixing ratio of corn straw and coal gangue 4:1, heating rate \( v = 20 \text{ K/min} \). The optimum combination test of combustible combustion is: oxygen concentration 30%, heating rate \( v = 10 \text{ K/min} \), mass mixing ratio of corn straw and coal gangue 2:3, and the combustible performance obtained by multi-factor orthogonal analysis has been significantly improved.

1. Introduction
At present, the coal-fired power generation plays a dominant role in Chinese electric power production. In recent years, there has been a nationwide shortage of the electricity supply. One of the main reasons for this situation is the tight supply of coal. Due to the continuous growth of the power demands and serious uneven distribution of the coal resources in the region, the situation of tight coal supply is difficult to be alleviated in the short term. Therefore, some power plants have to mix inferior fuels such as coal gangue and coal slurry [1-6]. Due to the inferior quality coal blending, the economic and safety of the boiler operation of the power station is seriously affected. In order to overcome the difficulties caused by the difference in coal quality and ensure the safe operation of the power plant, burning a certain amount of biomass fuel while burning coal gangue can significantly improve the operation of the power station boiler. For the way of coal gangue and biomass mixed combustion, scholars have carried out a lot of experimental researches.

Z Jianliang [7] et al. conducted nine different ratios of biomass and anthracite used non-isothermal thermogravimetric analysis, and the results show that the increase of biomass ratio in coal blending contributes to the combustion of fixed carbon, which is not conducive to the combustion of biomass volatiles. Varola M [8] et al. conducted a mixed combustion study on biomass and lignite used thermogravimetric analysis, it was found that the combustion characteristics of lignite can be improved after adding organisms. D Xinguang [9] et al. conducted a mixed combustion experiment of biomass and coal on a 400 t/h power station boiler, and obtained the most controllable factors for...
oxygen content in the operating state. M Fanfei [10] et al. studied the mixed combustion characteristics of biomass and various coal types using TG/DTG/DTA technology, which concluded that the combustion temperature can be lowered and the burning rate can be increased after adding biomass to lignite and bituminous coal. Gil M V [11] et al. used thermogravimetric analysis technology to carry out mixed combustion experiments on pine wood chips and bituminous coal, and the interactions between the raw materials and bituminous coal were not obvious.

However, the above studies only consider the influence of a single factor on the reaction process, and the synergy between factors cannot be considered, and cannot reflect the influence of multiple factors on blending combustion. Therefore, in order to better reflect the influence of multiple factors on blending combustion, and uses the orthogonal experiment method to discuss the synergy between factors to determine the optimal combination of experiments, and it is hoped to provide reference for practical application of power plant.

2. Experimental preparation

2.1. Experiment material
Corn straw and coal gangue obtained from Inner Mongolia Xilin Gol League were used as raw materials. The particle size of coal gangue and corn straw was 180-200 mesh and 100-120 mesh, respectively. Determination of the corn straw and coal gangue uses SDCHN series ultimate analyzer and SDLA718 proximate analyzer. Its ultimate analysis and proximate analysis are shown in Table 1.

| Proximate analysis Ultimate analysis |
|-------------------------------------|
| M_ad % | A_ad % | V_ad % | FC_ad % | C_ad % | H_ad % | O_ad % | N_ad % | S_ad % |
| Corn Straw | 1.93 | 8.63 | 72.74 | 18.10 | 58.37 | 3.44 | 37.85 | 0.87 | 0.12 |
| Coal Gangue | 0.58 | 52.50 | 12.56 | 34.42 | 44.85 | 5.93 | 6.18 | 1.19 | 0.11 |

2.2. Experimental contents and methods
This paper analyzes the mixed combustion of corn straw and coal gangue by using the Setsys Evo synchronous thermogravimetric analyzer. The mass of each test sample is about 10 mg, and the combustion test was carried out in an O_2/CO_2 atmosphere at a flow rate of 30 mL/min, and the combustion temperature ranged from the room temperature to final temperature of 1000 °C.

The purpose of the experimental is to improve the combustion performance of the corn straw and coal gangue. The combustion characteristic parameters such as the ignition index, flammability index, volatile matter precipitation index and comprehensive combustion characteristic index were characterized as the experimental indicators. In order to reduce the number of tests, and to ensure that the test results are representative, the orthogonal experiment method [12] is used in this paper. The first step in orthogonal experiment is to determine factors and levels. There are three factors influencing this experiment, atmosphere A, heating rate B and sample mass mixing ratio (corn straw: coal gangue) C. There are three levels under the A factor: 30% O_2 (A_1), 40% O_2 (A_2), 80% O_2 (A_3); and three levels of heating rate B factor [13]: 10 K/min (B_1), 20 K/min (B_2), 30 K/min (B_3); and three levels of sample mass mixing ratio C (corn straw: coal gangue): 2:3 (C_1), 3:2 (C_2), 4:1 (C_3). If all experiments are performed, 3^3=27 groups are required. In order to reduce the number of experiments, this paper chooses L_9 (3^4) [12] orthogonal table, and only need 9 experiments. The orthogonal experimental factor levels are shown in Table 2 and the experimental plan and results are shown in Table 3.
Table 2. Factor level table.

| Level | Factor | A (Oxygen Concentration) | B (Heating Rate K/min) | C (Mass Mixing Ratios) |
|-------|--------|--------------------------|------------------------|------------------------|
| 1     |        | 30%                      | 10                     | 2:3                    |
| 2     |        | 40%                      | 20                     | 3:2                    |
| 3     |        | 80%                      | 30                     | 4:1                    |

Table 3. Orthogonal experimental plan.

| Test Combinations |
|-------------------|
| A₁B₁C₁ A₂B₂C₂ A₃B₃C₃ |
| A₁B₂C₁ A₂B₃C₂ A₃B₃C₁ |
| A₁B₃C₁ A₂B₁C₂ A₃B₂C₁ |

The thermogravimetric analysis was performed on the determined nine combinations used a thermogravimetric analyzer to obtain the TG, DTG, and DTA curves for each combination. Analyzer the curve to obtain relevant characteristic parameters. The range and variance analysis of the orthogonal experiment are carried out with the combustion characteristic parameter values as the test indicators, and determine the optimal level of each indicator as the primary optimization process, and comprehensively consider each indicator to determine the optimal combustion conditions.

3. Analysis of experiment results

From the combustion curve of the coal gangue of Figure 1, the characteristic temperature and characteristic parameter values of coal gangue can be obtained as shown in Table 4.

Figure 1. Burning curves of coal gangue.

Table 4. Characteristics of coal gangue parameters.

| Sample            | Ignition Temperature Tᵢ (°C) | Burnout Temperature Tᵢ (°C) | (dw/dt)max (%•min⁻¹) | VT(1/2) | Peak Temperature T_max (°C) | (dw/dt)mean (%•min⁻¹) |
|-------------------|------------------------------|-----------------------------|-----------------------|---------|-----------------------------|----------------------|
| Coal Gangue       | 447                          | 733                         | 0.54                  | 116     | 531                         | 0.07                 |
3.1. Calculation of combustion performance parameters

Ignition index $D_i$: In order to evaluate the ignition characteristics, the ignition index $D_i$ is defined. The ignition index is determined by the ignition temperature $T_i$, the burnout temperature $T_f$, and the maximum weight loss rate $(dw/dt)_{\text{max}}$. Increasing the ignition index indicates the improved ignition performance of the improved ignition. The ignition index can be obtained by the formula (3.1) [14]:

$$D_i = \frac{(dw/dt)_{\text{max}}}{T_i \times T_f} \quad (3.1)$$

Flammability index $C$: The flammability index refers to the ability of the combustion reaction to ignite, reflecting the changes from the ignition temperature to the maximum peak point of the DTG, which characterizes the ignition stability of the pre-combustion process. Flammability index $C$ can represent the difficulty degree of the ignition process, which is positively correlated with the ignition stability. $T_i$ indicates the ignition temperature of the sample, which is the maximum burning speed. The higher the flammability index is, the better the flammability and ignition stability of the sample will be. The flammability index can be obtained by the formula (3.2) [14]:

$$C = \frac{(dw/dt)_{\text{max}}}{T_i^2} \quad (3.2)$$

Volatile matter precipitation index $D$: The volatile matter precipitation characteristics play an important role in pre-combustion and post-combustion. The parameters that reflect the volatile matter precipitation characteristics are Volatile matter precipitation index $D$ and maximum precipitation rate $(dw/dt)_{\text{max}}$. From the parameters of the TG curve of the combustion weight loss, the volatile matter precipitation index $D$ can be calculated by the formula (3.3). Where, $(dw/dt)_{\text{max}}$ represents the maximum precipitation rate of the volatile matter at the maximum value of DTG, $T_{\text{max}}$ represents the temperature corresponding to the maximum value of DTG, and $\nabla T(1/2)$ indicates that the precipitation rate is not less than $1/2(dw/dt)_{\text{max}}$.

$$D = \frac{(dw/dt)_{\text{max}}}{T_{\text{max}} \nabla T(1/2)} \quad (3.3)$$

Comprehensive combustion characteristic index $S$: The comprehensive combustion characteristic index can indicate the comprehensive combustion characteristics of the sample combustion. The comprehensive combustion characteristic index $S$ comprehensively considers the ignition characteristics and the burnout characteristics, and is an indicator of the advantages and disadvantages of the combustion process. The larger $S$, the better the comprehensive combustion characteristics of the sample. The comprehensive combustion characteristic index can be obtained by the formula (3.4) [6]:

$$S = \frac{(dw/dt)_{\text{max}} \times (dw/dt)_{\text{mean}}}{T_i^2 \times T_f} \quad (3.4)$$

The characteristic values of the characteristic temperature and the characteristic parameters obtained in Table 4 are substituted into the formulas (3.1), (3.2), (3.3), and (3.4) to obtain the combustion characteristic index values, which are as shown in Table 5.

| Sample       | $D_i \times 10^6$ | $C \times 10^6$ | $D \times 10^6$ | $S \times 10^6$ |
|--------------|------------------|----------------|----------------|----------------|
| Coal Gangue  | 1.63             | 2.68           | 8.62           | 2.47           |
3.2. Experiment result analysis

3.2.1. Preliminary selection of optimization process. Combustion experiments were performed on nine experimental combinations in a thermogravimetric analyzer to obtain TG, DTG and DTA curves for each combination. Through the analysis of the curve, the ignition temperature, burnout temperature, peak temperature, of each experimental combination can be obtained. Further, the ignition index $D_i$, the flammability index $C$, the volatile matter precipitation index $D$, and the comprehensive combustion characteristic index $S$ can be obtained. The calculation results are shown in Table 6.

| Table 6. The experiment result. |
| --- |
| Factor | Group | Oxygen Concentration | Heating Rate (K/min) | Mass Mixing Ratios | $D_i \times 10^6$ (%•min$^{-1}$•℃$^{-2}$) | $C \times 10^6$ (%•min$^{-1}$•℃$^{-2}$) | $D \times 10^6$ (%•min$^{-1}$•℃$^{-2}$) | $S \times 10^{10}$ (%•min$^{-2}$•℃$^{-2}$) |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1 | A$_1$B$_1$C$_1$ | 30% | 10 | 2:3 | 12.04 | 17.67 | 34.42 | 200.8 |
| 2 | A$_1$B$_2$C$_2$ | 30% | 20 | 3:2 | 4.51 | 11.85 | 18.24 | 27.6 |
| 3 | A$_1$B$_3$C$_3$ | 30% | 30 | 4:1 | 5.33 | 16.06 | 20.91 | 54.09 |
| 4 | A$_2$B$_1$C$_2$ | 40% | 10 | 3:2 | 2.45 | 6.32 | 8.91 | 2.9 |
| 5 | A$_2$B$_2$C$_3$ | 40% | 20 | 4:1 | 7.22 | 18.38 | 27.72 | 41.57 |
| 6 | A$_2$B$_3$C$_1$ | 40% | 30 | 2:3 | 2.31 | 4.85 | 1.94 | 14.18 |
| 7 | A$_3$B$_1$C$_3$ | 80% | 10 | 4:1 | 3.82 | 8.05 | 16.66 | 12.83 |
| 8 | A$_3$B$_2$C$_1$ | 80% | 20 | 2:3 | 4.32 | 10.77 | 27.93 | 17.12 |
| 9 | A$_3$B$_3$C$_2$ | 80% | 30 | 3:2 | 6.20 | 14.73 | 28.65 | 55.35 |

In order to get the relationship between the influence of each factor on the experiment, this paper uses the range analysis method to calculate the test data. The range $R$ can reflect the influence of this factor on the indicator. The greater the range $R$, the greater the influence of this factor on the indicator. The range $R$ can be calculated from equation (3.5) [12].

$$ R = \max(I_1, I_2, I_3, \cdots) - \min(I_1, I_2, I_3, \cdots) $$ (3.5)

$I_1, I_2, I_3, \cdots$ denotes the sum of the indices corresponding to the number "1" in each $i$-th column, the sum of the indices corresponding to the number "2" in each $i$-th, …

At each level of each factor, the range calculation is performed for the ignition index $D_i$, the flammability index $C$, the volatile matter precipitation characteristic index $D$, and the comprehensive combustion characteristic index $S$. The calculation results are shown in Table 7.

| Table 7. Analysis of the index range in orthogonal experiment. |
| --- |
| Factor | Result | \(D_i \times 10^6\) (%•min$^{-1}$•℃$^{-2}$) | \(C \times 10^6\) (%•min$^{-1}$•℃$^{-2}$) | \(D \times 10^6\) (%•min$^{-1}$•℃$^{-2}$) | \(S \times 10^{10}\) (%•min$^{-2}$•℃$^{-2}$) |
| --- | --- | --- | --- | --- | --- |
| Oxygen Concentration | | 21.88 | 22.95 | 20.52 | 23.43 | 23.52 | 24.37 | 25.23 | 26.10 |
| Heating Rate | | 18.31 | 18.50 | 18.29 | 18.60 | 18.70 | 18.89 | 19.09 | 19.28 |
| Mass Mixing Ratios | | 18.67 | 18.70 | 18.50 | 18.70 | 18.89 | 19.10 | 19.30 | 19.50 |

Comparing the range of each level under each factors, the preliminary selection process table of each performance influencing factor is obtained, as shown in Table 8.

3.2.2. Optimal process combination. Since the optimization conditions in Table 8 are different from the four test indicators, it is necessary to comprehensively consider to determine the optimal combination.

The comprehensive combustion performance, ignition performance, flammability performance and volatile analysis performance were analyzed and summarized. The results are shown in Table 9.
Comprehensive analysis shows that Oxygen concentration 30%, heating rate $v=20$ K/min, and mass mixing ratios (corn straw: coal gangue) 4:1 are the optimal combinations.

**Table 8.** Preliminary selection of optimization process polar.

| Experimental Index               | Prioritization                                           | Oxygen Concentration | Heating Rate (K/min) | Mixing Ratios |
|----------------------------------|----------------------------------------------------------|----------------------|----------------------|---------------|
| Comprehensive Combustion Index   | Oxygen Concentration > Mass Mixing Ratios > Heating Rate| 30%                  | 10                   | 2:3           |
| Ignition Index                   | Oxygen Concentration > Mass Mixing Ratios > Heating Rate| 30%                  | 10                   | 2:3           |
| Flammability Index               | Oxygen Concentration > Mass Mixing Ratios > Heating Rate| 30%                  | 20                   | 4:1           |
| Volatile Matter Precipitation Index | Oxygen Concentration > Mass Mixing Ratios > Heating Rate| 30%                  | 20                   | 4:1           |

**Table 9.** Preliminary selection of optimization process variance.

| Experimental Index             | Particularly Significant Impact | Very significant impact | Make a Difference | No Effect |
|--------------------------------|---------------------------------|-------------------------|-------------------|-----------|
| Comprehensive Combustion Index | -                               | -                       | ✓ (Oxygen Concentration) | -         |
| Ignition Index                 | -                               | ✓ (Oxygen Concentration)| -                 | -         |
| Flammability Index             | -                               | -                       | -                 | -         |
| Volatile Matter Precipitation Index | ✓ (Oxygen Concentration) | ✓ (Heating Rate) | -                 | -         |

The comparison of the best single factor experiment conditions obtained by the single factor and the combustion performance of the optimal combination obtained by multivariate orthogonal test are shown in Table 10:

**Table 10.** Comparison of combustion performance parameters.

| Sample                                           | $D \times 10^6$ | $C \times 10^6$ | $D \times 10^6$ | $S \times 10^6$ |
|--------------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Coal Gangue                                      | 1.63            | 2.68            | 8.62            | 2.47            |
| 40% O$_2$ Mass Mixing Ratios (Corn Straw: Coal Gangue) = 3:2 | 4.44            | 1.32            | 3.12            | 2.36            |
| Heating Rate $v=30$ k/min                        | 7.70            | 19.04           | 39.30           | 41.54           |
| Optimal Combination                              | 2.72            | 10.70           | 13.80           | 22.50           |
| Note: 40% O$_2$, mass mixing ratios (corn straw: coal gangue) = 3:2, heating rate $v=30$ K/min is the best experimental condition obtained by the single factor analysis. | 12.04           | 17.67           | 34.42           | 200.80          |
From the results of the above table and the results of combustion of coal gangue alone, a comparative analysis can be obtained:

At the optimum Oxygen concentration (40% O₂), the ignition performance of the sample increased by 1.72 times compared with the pure coal gangue.

At the optimum blending ratio, the ignition performance, flammability, volatile matter precipitation performance and comprehensive combustion performance of the sample are increased by 3.72 times, 6.1 times, 3.57 times and 15.82 times, respectively, which are compared with the pure coal gangue.

At the optimum heating rate, the ignition performance, flammability, volatile matter precipitation performance and comprehensive combustion performance of the sample are increased by 0.67 times, 3 times, 0.61 times and 8.1 times respectively compared with pure coal gangue.

At the optimal combination, the ignition performance, flammability, volatile matter precipitation performance and comprehensive combustion performance of the sample are increased by 6.38 times, 5.59 times, 3 times and 81.29 times, respectively, compared with pure coal gangue.

Gil M V [11] et al. conducted mixed combustion experiments with pine wood chips and bituminous coal, and found that pine wood chips and bituminous coal did not show significant effects when mixed combustion. This may be because bituminous coal is a high-quality coal type, the fixed carbon content and volatile matter content are much larger than, and the ash content is much smaller than the coal gangue used in this experiment. This will result in no significant effect on bituminous coal after the addition of the organism.

Therefore, the optimal combination obtained by the multi-factor orthogonal experiment has a significant influence on the combustion performance compared with the single factor change.

4. Conclusions

The following conclusions can be drawn from the above experiments and analysis:

The optimal combination of comprehensive combustion performance and ignition performance is 30% Oxygen concentration, mass mixing ratio (corn straw: coal gangue) 2:3, heating rate \( v=10 \) K/min.

The combination of the flammability and volatile matter precipitation performance is 30% Oxygen concentration, mass mixing ratio (corn straw: coal gangue) 4:1, heating rate \( v=20 \) K/min.

The results of the variance analysis show that the influence of the Oxygen concentration on each test index is the main factor. Considering the influence of various factors, the optimal combination is 30% Oxygen concentration, mass mixing ratios (corn straw: coal gangue) 2:3, heating rate \( v=10 \) K/min;

The results of multi-factor orthogonal experimental analysis are more significant than the single factor improvement.

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