

Study on the Circulating Fluidized Bed Co-Combustion of Coal Gasification Slag and Coal Coking Dedusting Ash

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ABSTRACT: Coal-based chemical industries generate large amounts of coal gasification slag (CGS), including coarse slag (CGCS) and fine slag (CGFS), and coal coking dedusting ash (CCDA). CGFS is wet, fine, carbon-rich but difficult to ignite; CGCS has low carbon and calorific value; CCDA is high-carbon and anthracite-like but too fine for metallurgical use. This study proposes and validates circulating fluidized bed (CFB) co-firing of CGS and CCDA. Three cases were tested: Case I, CGFS alone; Case II, CGCS + CCDA ($\approx 1800 \text{ kcal}\cdot\text{kg}^{-1}$); and Case III, CGFS ($\approx 30\%$ moisture) + CGCS + CCDA ($\approx 1800 \text{ kcal}\cdot\text{kg}^{-1}$). A 2 MWh CFB pilot platform was used to evaluate operational stability, ash characteristics, emissions, and combustion efficiency. The ternary blend showed a potential synergistic effect: its apparent activation energy was only $95.8 \text{ kJ}\cdot\text{mol}^{-1}$, lower than $157.7 \text{ kJ}\cdot\text{mol}^{-1}$ for CGFS and $115.1 \text{ kJ}\cdot\text{mol}^{-1}$ for CGCS + CCDA. All cases achieved stable feeding, unobstructed circulation, and uniform temperature distribution, with fluctuations within 50°C for Case I and 20°C for Cases II and III. Raw flue-gas concentrations were NO_x 20–60 ppm, SO_2 70–180 ppm, and CO 500–850 ppm; after normalization to 6% O_2 , SO_2 was 255.5–492.0 mg/Nm^3 and NO_x (as NO_2) 56.5–108.8 mg/Nm^3 , exceeding regulatory limits, so flue-gas cleaning is required. Combustion efficiencies reached 83.86–92.53%, and fly-ash carbon/ash ratios were 0.047, 0.061, and 0.035. The innovation lies in using high-carbon CCDA to compensate for low-calorific CGCS and difficult ignition of CGFS, while high-reactivity CGFS and ternary blending improve burnout. Preliminary scheme-level TEA for Case III (400,000 $\text{t}\cdot\text{a}^{-1}$, 8,000 $\text{h}\cdot\text{a}^{-1}$) estimates $\sim 9.3\times 10^4 \text{ tce}\cdot\text{a}^{-1}$ saved, 7.8×10^5 – $8.3\times 10^5 \text{ t}\cdot\text{a}^{-1}$ steam, direct CO_2 $2.52\times 10^5 \text{ t}\cdot\text{a}^{-1}$, avoided CO_2 $2.71\times 10^5 \text{ t}\cdot\text{a}^{-1}$, and net reduction $\sim 1.9\times 10^4 \text{ t}\cdot\text{a}^{-1}$; ash mineralization potential is 0.9×10^4 – $3.0\times 10^4 \text{ t CO}_2\cdot\text{a}^{-1}$. Estimated revenue is CNY 110–200 million $\cdot\text{a}^{-1}$ with a 4–7-year payback. CFB co-firing is therefore a feasible and promising route for CGS and CCDA utilization.

Keywords: Waste utilization, Coal gasification slag, Coal coking dedusting ash, Circulating fluidized bed, Combustion efficiency, Coal conversion, NO_x , SO_2 and CO emissions.

1. INTRODUCTION

Coal gasification slag (CGS) is a by-product of the coal gasification process. China generates over 70 million tons of CGS annually [1, 2], and this amount continues to grow [3]. CGS can be divided into coal gasification

coarse slag (CGCS) and coal gasification fine slag

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(CGFS) [4]. Currently, non-fuel utilization pathways for CGS mainly include cement and concrete admixtures, lightweight aggregates, adsorbents, catalyst supports, porous materials, and carbon-ash separation [1, 4-6]. However, these pathways generally suffer from high cost, complex processes, limited consumption capacity, low added value of building materials, and functional materials that are mostly at the laboratory or pilot scale [5, 6]. Therefore, non-fuel utilization alone cannot consume CGS on a large scale, and combustion or co-combustion remains an important option.

CGCS has high mineral content, low carbon content, low calorific value [7, 8], and is difficult to burn, making it difficult to use directly as fuel. CGFS contains 10–40% residual carbon [9], but has low volatile matter, low combustion rate, and poor combustion performance [10]. In addition, it has a fine particle size, well-developed pores, strong water absorption, and is difficult to dewater; its moisture content remains about 30% after industrial dewatering [11]. Co-combustion with coal, biomass, or sludge can significantly improve its ignition and burnout characteristics [3, 12, 13]. Pilot-scale tests of fluidized melting combustion showed that the preheating stage can achieve dehydration, preheating, and crushing of CGFS [14]. Mild oxidation can reduce the activation energy of CGFS residual carbon and narrow its combustion temperature range [9]. Studies on pressurized gasification fine slag indicate that ash-induced mass transfer limitation is the dominant factor of combustion inertness, leading to difficult ignition, low burnout, and high slagging tendency [8, 10]. Blending gasification fine slag in a CFB has been proven feasible, with small changes in bed temperature, flue gas oxygen content, and bed differential pressure [3, 14]. However, achieving stable feeding and ignition in a CFB remains challenging. In addition, the formation of gaseous pollutants such as NO_x , SO_2 , and CO during such combustion processes has also attracted attention; the conversion of fuel nitrogen to NO_x is influenced by local O_2 concentration and char concentration [14], while incomplete combustion tends to produce CO [15].

Coal coking dedusting ash (CCDA) is a by-product collected during coke production [16], with a yield of about 4% of coke output [17, 18]. Based on the scale of China's coking industry [19-21], its annual output is at least tens of millions of tons. CCDA is coke-like, with high carbon, low volatile matter, and high calorific value, and its properties are close to those of anthracite. CCDA can partially replace anthracite for blast furnace injection, but its fine particles and low mechanical strength limit its

large-scale metallurgical utilization [22]. Currently, research on direct combustion of CCDA is still limited. Studies have proposed injecting CCDA into high-temperature converter flue gas to produce CO-rich gas [16]. By analyzing the technical feasibility of replacing part of the high-cost anthracite with coke dry quenching (CDQ) dust in terms of burnout rate, grindability, and ignition point, the results showed that its combustion performance is poorer than that of anthracite [23]. Its combustion may also release SO_2 depending on sulfur content and occurrence mode [24]. From a combustion perspective, CCDA can serve as a high-calorific component, but its dense carbon structure may hinder ignition and burnout.

This study proposes a technical concept of co-firing low-calorific gasification slag with high-calorific dedusting ash. In summary, this concept aims to use the high calorific value of CCDA to compensate for the low calorific value of CGCS/CGFS, use the highly reactive residual carbon of CGFS to improve the poor burnout of CCDA, and achieve stable combustion and provide a basis for subsequent emission control through ternary blending in a CFB. Based on this, the main difficulties are: (i) CGFS has high moisture content, fine particle size, and low volatile matter, making feeding, ignition, and stable combustion difficult; (ii) CGCS has low calorific value and poor combustion performance; (iii) CCDA has a dense carbon structure and poor reactivity; (iv) the synergistic effects among CGFS, CGCS, and CCDA remain unclear; (v) the coordinated control of stable operation, high combustion efficiency, and pollutant emissions under ternary blending conditions needs to be investigated.

To address these difficulties, pilot-scale tests were conducted on a 2 MWh CFB platform. The main work includes: (i) designing three cases—Case I (CGFS alone), Case II (CGCS+CCDA), and Case III (CGFS+CGCS+CCDA)—to investigate the effects of blending on ignition, stable combustion, and burnout; (ii) evaluating operational stability, temperature distribution, ash characteristics, gaseous emissions, and combustion efficiency; (iii) measuring NO_x , SO_2 , and CO to analyze their formation characteristics and provide data for low- NO_x combustion and desulfurization; (iv) combining thermogravimetric analysis, apparent activation energy calculation, and ash composition analysis to reveal synergistic effects and explore the possible catalytic roles of CaO and Fe_2O_3 ; (v) verifying technical feasibility and providing basic data for industrial demonstration and economic analysis.

2. MATERIAL AND METHOD

2.1. Fuel Samples

The experimental fuels were CGFS, CGCS, and CCDA from the Huaibei Mining Group. Among them, the CGFS had a moisture content as high as over 50%, making feeding and ignition difficult. By controlling the drying time, the moisture content of the CGFS fed into the furnace was maintained at around 30%.

Three fuel cases were set up: Case I combustion of CGFS alone; Case II, combustion of a binary mixture of 75 wt.% CGCS and 25 wt.% CCDA, with a calorific value of about $1800 \text{ kcal} \cdot \text{kg}^{-1}$; Case III, combustion of a ternary mixture of 34 wt.% CGFS ($\approx 30\%$ moisture), 51 wt.% CGCS, and 15 wt.% CCDA, also with a calorific value of about $1800 \text{ kcal} \cdot \text{kg}^{-1}$.

The results of proximate analysis, ultimate analysis, calorific value, and ash composition analysis for the fuels of each case are shown in Tables 1 and 2, respectively. Sampling was done by taking multiple small samples from different points, mixing them evenly, and then selecting representative samples, ensuring relatively stable and average properties with good representativeness.

2.2. Experimental Platform

The experiments were conducted on a 2 MWth circulating fluidized bed (CFB) pilot combustion facility (Figure 1). The pilot plant mainly consists of a combustion furnace, a cyclone separator, a solid particle return system, tail-end heating exchange surfaces, air/flue gas systems, an igniter, a fuel feeder, and other components. The combustion furnace has a square cross-section and is divided into two sections. The total height of the furnace is 20 m. The lower wind box distributor plate measures $370 \times 370 \text{ mm}$, and the internal dimensions of the upper furnace section are $480 \text{ mm} \times 480 \text{ mm}$. Along the furnace height, there are fuel feed, secondary air input, temperature measurement points, sampling ports, and pressure measurement ports. An ash discharge pipe, temperature and pressure measurement ports are installed on the bottom wind box, which is integrated with the ignition section.

Considering the special properties of CGFS, such as small particle size, high moisture content, and low calorific value, modifications were made to the existing CFB combustion facility, including:

- (1) Installing a burnout chamber after the separator exhaust outlet to allow further complete combustion of

Table 1: Proximate and ultimate analyses of samples

Sample		Proximate analysis (wt.ad%) ^a					Ultimate analysis (wt.ad%) _{ad}					$Q_{\text{net,ar}}(\text{kcal} \cdot \text{kg}^{-1})$
		M	A	V	FC	M_{ar}	C	H	N	S	O ^b	
Raw sample	CGFS	1.44	60.75	1.78	36.03	28.63	34.73	0.26	0.20	0.24	2.38	2137
	CGCS	0.59	92.62	0.57	6.22	9.02	6.15	0.11	0.16	0.26	0.20	483
	CCDA	0.69	23.66	3.42	72.23	1.91	70.83	0.31	0.80	1.21	2.50	5851
Treated sample	Case I	1.44	60.75	1.78	36.03	28.63	34.73	0.26	0.20	0.24	2.38	2137
	Case II	0.66	71.49	1.31	26.54	5.15	22.12	0.19	0.22	0.52	4.31	1867
	Case III	1.11	71.39	0.96	26.54	16.40	22.54	0.22	0.22	0.30	4.34	1783

^a ad, air dry basis; ar, as received basis; ^b by difference.

Table 2: Ash composition analysis of samples

Content (%)		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O
Raw sample	CGFS	52.62	18.72	8.60	4.89	7.34	1.72	5.05
	CGCS	50.84	17.52	10.25	6.34	6.21	1.55	4.08
	CCDA	33.81	19.52	10.65	12.94	8.79	0.65	3.05
Treated sample	Case I	52.62	18.72	8.60	4.89	7.34	1.72	5.05
	Case II	47.90	19.30	10.64	8.64	6.21	0.98	3.18
	Case III	48.01	18.76	11.48	7.94	5.18	1.31	5.16

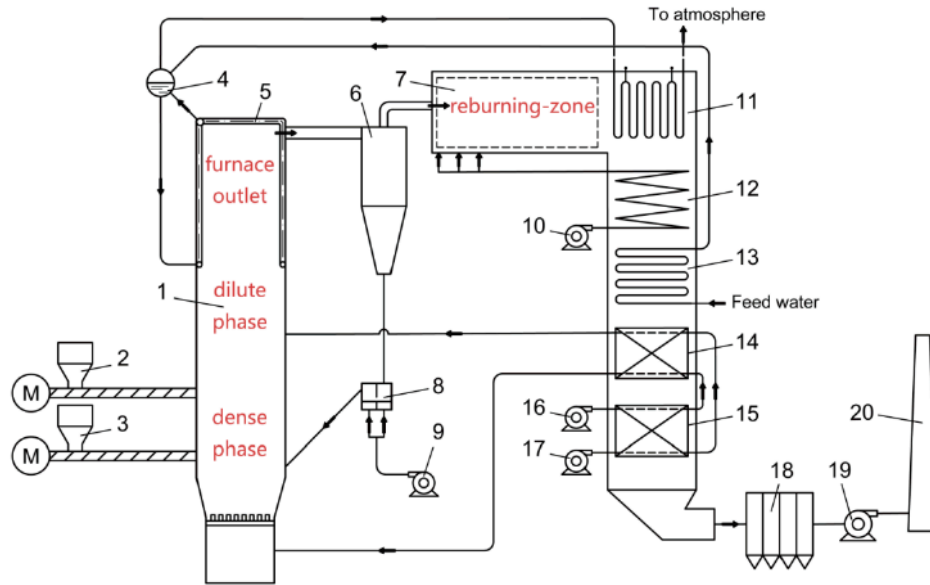


Figure 1: Schematic diagram of 2MW circulating fluidized bed combustion test platform.

unburned carbon-containing fly ash, ensuring high combustion efficiency.

(2) Adding a burnout air preheater in the tail flue to increase the temperature of the combustion air, thereby improving combustion rate and enhancing combustion stability.

The operating parameters (temperature, pressure, flow rate, feed rate, etc.) of the experimental system were

sent to a computer via the DCS system, enabling online data display and storage (Figure 2). The key operating parameters of this experiment are shown in the Table 3.

1-Circulating Fluidized Bed (CFB) Combustor ; 2-Bed Material Feeding System ; 3-Fuel Feeding System ; 4-Steam Drum ; 5-Waterwall Tubes ; 6-Cyclone Separator ; 7-Reburner ; 8-Loop Seal ; 9-Roots Blower ; 10-Reburn Air Fan ; 11-Superheater ; 12-Reburn Air Preheater ; 13-Economizer ; 14-Secondary

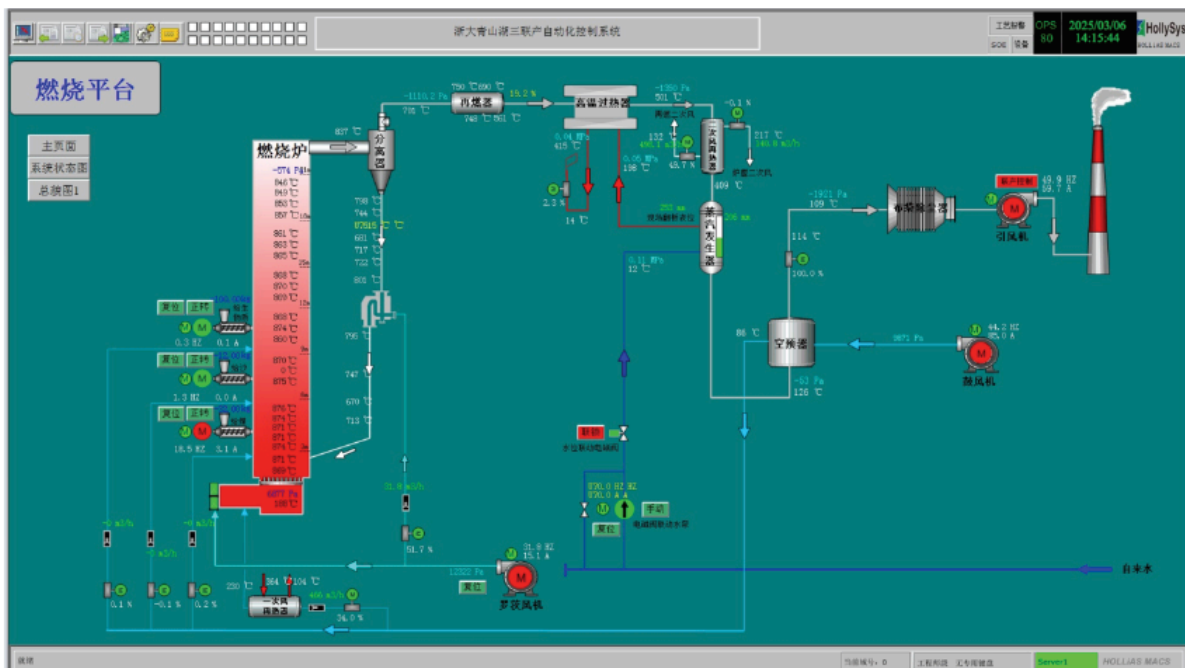


Figure 2: DCS Control System Operating Interface.

Air Preheater ; 15-Primary Air Preheater ; 16-Primary Air Fan ; 17-Secondary Air Fan ; 18-Flue Gas Cleaning System ; 19-Induced Draft (ID) Fan ; 20-Flue Gas Exhaust System

Table 3: Key operating parameters

Parameter	Unit	Value
Feed Rate	kg·h ⁻¹	Adjusted in real-time to maintain stable combustion during operation
Furnace Temperature	°C	800-900
Reburning Temperature	°C	600-700
Oxygen Content in Flue Gas	%	4-8

■ 2.3. Sampling and Analysis Method

Fuel entering the furnace was sampled every 10 minutes, and samples for each case were accumulated into a composite sample, from which a representative sub-sample was taken according to sample splitting principles. Fly ash samples from the flue gas were collected isokinetically using a 3012H automatic dust tester in the flue before the baghouse filter, with sampling every 30 minutes. Bottom slag samples were discharged from the bottom of the fluidized bed, maintaining essentially constant wind box pressure, and sampled every 30 minutes. Composite slag samples for each case were obtained by sample splitting. Flue gas composition and concentration after combustion were monitored on-site using a HORIBA-PG-300 compact and lightweight gas analyzer in the flue before the baghouse filter.

Sampled fuel was placed in an oven, dried at 105°C for 3 hours, and then subjected to particle size analysis, BET pore structure and specific surface area analysis, SEM analysis, XRF analysis, and thermogravimetric analysis (TGA). Collected fly ash and bottom slag were also dried at 105°C for 3 hours and then analyzed for carbon content, particle size, BET pore structure, and SEM.

The specific surface area and total pore volume of the sampled fuels were measured using an American Micromeritics ASAP2460 automatic surface area and porosity analyzer.

Thermogravimetric analysis of the sampled fuels was performed using an STA449F3 simultaneous thermal analyzer. The experiments were conducted under atmospheric pressure, with an initial temperature of 30°C, a heating rate of 20°C·min⁻¹, up to a final temperature of

1000°C. The atmosphere was air with a flow rate of 50 mL·min⁻¹. thermogravimetry (TG) and derivative thermogravimetry (DTG) curves of the sampled fuels were obtained.

■ 2.4. Combustion Efficiency Calculation

After obtaining data such as the bottom slag fraction (α_{sl}), slag carbon content (C_{sl}), fly ash fraction (α_{fa}), and fly ash carbon content (C_{fa}), the uncompletely combustion loss of gas (q_3), the uncompletely combustion loss of carbon (q_4), and the combustion efficiency (η_c) for each experimental case was calculated using the following main formulas.

$$q_3 = 12640 \times \text{CO} \times V_f / Q_{\text{net,ar}} \quad (1)$$

$$q_4 = 32780 \times (\alpha_{fa} C_{fa} + \alpha_{sl} C_{sl}) / Q_{\text{net,ar}} \quad (2)$$

$$\eta_c = 100 - q_3 - q_4 \quad (3)$$

where q_3, q_4 , and η_c are in %; CO is the measured CO concentration in the flue gas, in vol.%, and should be inserted as a percentage value, e.g., 500 ppm = 0.05 vol.%; V_f is the dry flue gas volume per unit mass of fuel, in m³·kg⁻¹; $Q_{\text{net,ar}}$ is the net calorific value of the fuel as received, in kJ·kg⁻¹. In the foregoing text and tables, $Q_{\text{net,ar}}$ is expressed in kcal·kg⁻¹; in these equations it is converted to kJ·kg⁻¹ using 1 kcal = 4.1868 kJ. α_{fa} and α_{sl} are the mass fractions of ash in the fly ash and bottom slag, respectively, dimensionless and $\alpha_{fa} + \alpha_{sl} = 1$; C_{fa} and C_{sl} are the carbon contents of fly ash and bottom slag, respectively, in wt.%. The constants 12640 kJ·m⁻³ and 32780 kJ·kg⁻¹ are the heats of combustion of CO and carbon, respectively.

■ 3. RESULTS AND DISCUSSION

■ 3.1. Sample Characterization

■ 3.1.1. Particle Size and Pore Structures

Particle size data for the fuels of the three cases were obtained using a Malvern particle size analyzer. Case I fuel (pure CGFS) had the smallest overall particle size, with most particles below 120 µm, and the volume fraction curve showed a bimodal distribution, with an average particle size of 58.48 µm. Case II fuel (CGCS mixed with CCDA) had the largest overall particle size, with the peak volume fraction around 200 µm, and the volume fraction curve was essentially unimodal, with an average particle size of 212.17 µm. Case III fuel (mixture of CGFS, CGCS, and CCDA) had an overall particle size between Cases I and II, with a bimodal volume fraction

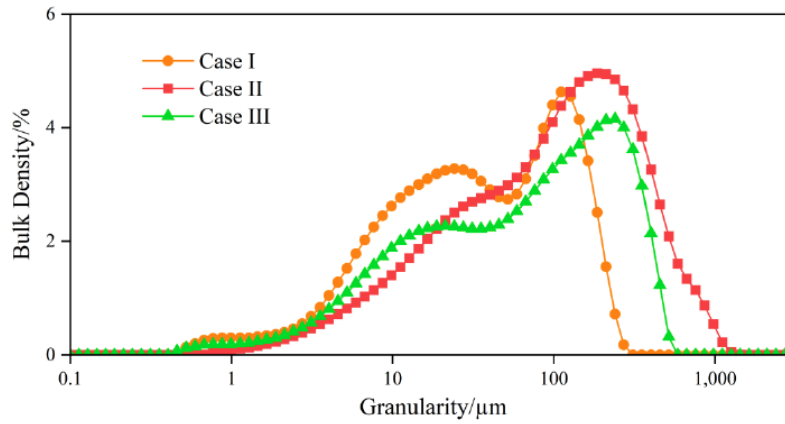


Figure 3: Fuel particle size distribution.

curve (less pronounced than Case I), and an average particle size of 115.62 μm .

The specific surface area and total pore volume of the fuels were measured using an American Micromeritics ASAP2460 automatic surface area and porosity analyzer; results are shown in Table 4. Case I (pure CGFS) fuel had the largest particle specific surface area and total pore volume among the three groups, significantly larger than the others. Case II (CGCS and CCDA mixture) fuel had the smallest particle specific surface area and total

pore volume. Case III (ternary mixture) fuel had values intermediate between the first two. A larger specific surface area and pore volume facilitate the diffusion of external oxygen into the particle interior, promoting the combustion reaction, while smaller values hinder the combustion reaction.

SEM analysis was performed on the different fuels; results are shown in Figure 4. Most particles in the fuels were fine spherical or near-spherical particles in the micrometer size range, with relatively smooth surfaces,

Table 4: Fuel specific surface area and total pore volume

Parameter / Unit	Case I	Case II	Case III
$S_p/\text{m}^2\cdot\text{g}^{-1}$	231.6787	16.3739	122.9612
$V_p/\text{cm}^3\cdot\text{g}^{-1}$	0.249659	0.020964	0.134682

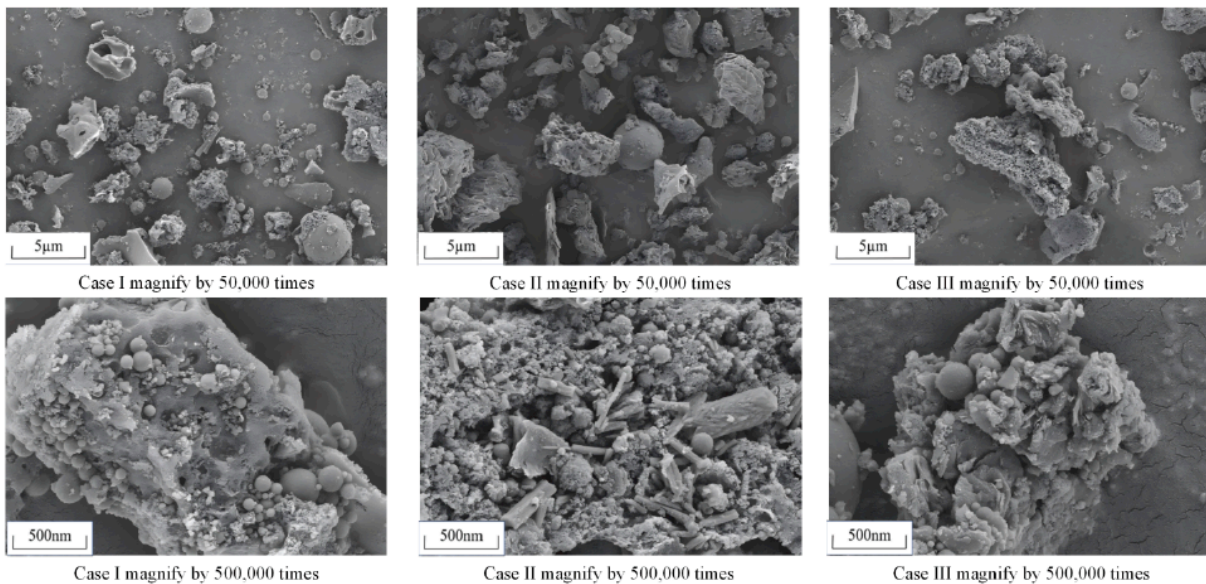


Figure 4: SEM images of different fuels.

possibly formed by the melting, aggregation, and contraction under surface tension of minerals during gasification. The particle surfaces contained numerous pores of varying sizes, from nanometers to micrometers. These pores might be formed by gas escape during gasification or left after the decomposition of organic matter. Some particle surfaces were rough, with obvious cracks and pits. Cracks might be caused by thermal stress, while pits could result from the volatilization of certain components or the precipitation of reaction products during gasification. Some particle surfaces were relatively smooth, possibly glassy substances formed during gasification, with dense surfaces and no obvious pores. Due to the blending with CCDA, blocky and strip-like structures were observed. The edges of these structures were usually sharp, with uneven surfaces showing obvious cracks and fracture planes. Graphitized structures, manifested as parallel-arranged graphite layers, were also observed.

3.1.2. Thermogravimetric Analysis

Thermogravimetric analysis was performed on the different fuels, yielding thermogravimetry (TG) and derivative thermogravimetry (DTG) curves. From the TG curves, Case I had the largest weight loss, while Case II and III had similar final weight losses but different weight loss processes. The DTG curves for Cases I and II showed a single peak. Case I had a lower temperature for the weight loss peak, which was significantly higher. Case III fuel contained components from both Case I and Case II, and its DTG curve showed a bimodal distribution, with the lower temperature peak significantly higher than the higher temperature peak. The ignition temperatures for the fuels of Cases I, II, and III were 595.7°C, 637.6°C, and 594.8°C, respectively, and the burnout temperatures were 687.8°C, 802.5°C, and 807.6°C, respectively. Overall, Case I had the best combustion performance, followed by Case III, and Case II had the poorest.

The apparent activation energies (E_a) calculated by the Coats–Redfern method were 157.7 kJ·mol⁻¹, 115.1 kJ·mol⁻¹, and 95.8 kJ·mol⁻¹ for the three cases, respectively. The fitting reaction order was 1 for all three cases, and the coefficient of determination (R^2) was greater than 0.98 in all cases, indicating that the Coats–

Redfern fitting results are reliable. The corresponding fitting parameters are summarized in Table 5.

Case I had the lowest ignition temperature and the largest weight loss because CGFS contains abundant residual carbon with a well-developed pore structure ($S_p=231.68 \text{ m}^2\cdot\text{g}^{-1}$; $V_p=0.249659 \text{ cm}^3\cdot\text{g}^{-1}$), which favors oxygen diffusion and initial ignition. Case II showed the highest ignition temperature and the poorest burnout because CGCS has a low calorific value and CCDA has a dense, anthracite-like carbon structure with low reactivity; moreover, the blended fuel had the largest mean particle size (212.17 μm) and the lowest specific surface area and pore volume. Case III exhibited the lowest E_a (95.8 kJ·mol⁻¹), which may indicate a possible synergistic effect. This can be explained by three factors: (i) the highly reactive residual carbon in CGFS promotes initial ignition; (ii) CCDA supplies high-carbon fuel and heat; and (iii) minerals such as CaO and Fe₂O₃ in the ash may catalyze char oxidation and oxygen transfer [26]. Although the burnout temperature of Case III was slightly higher than that of Case I due to the dense carbon in CCDA, the lower E_a means that the ternary blend can be ignited and maintained more easily. The practical benefit is improved fuel flexibility and reduced ignition-support requirements for low-calorific, high-moisture, and difficult-to-burn wastes.

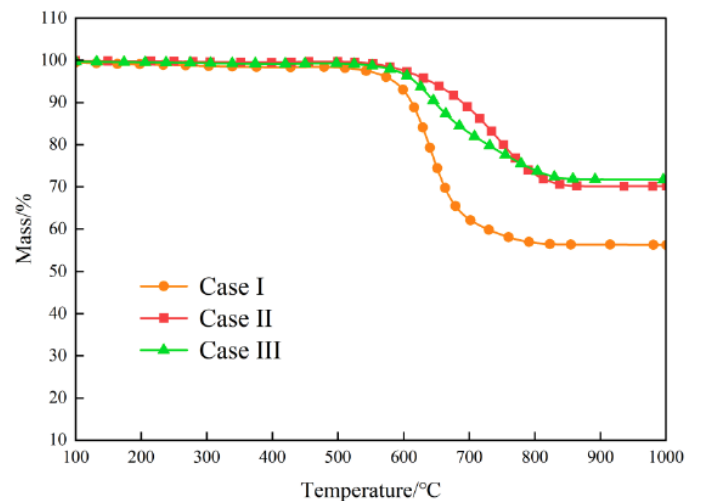


Figure 5: Fuel TG curves.

Table 5: Coats–Redfern fitting parameters for the three cases

Case	Fitting range/°C	Fitting equation	R^2	E_a / kJ·mol ⁻¹	A/min^{-1}
I	580-700	$y=-18967x+6.6513$	0.988	157.7	293529.34
II	600-850	$y=-13849x-0.1497$	0.997	115.1	238.47
III	580-820	$y=-11526x-2.1281$	0.990	95.8	27.44

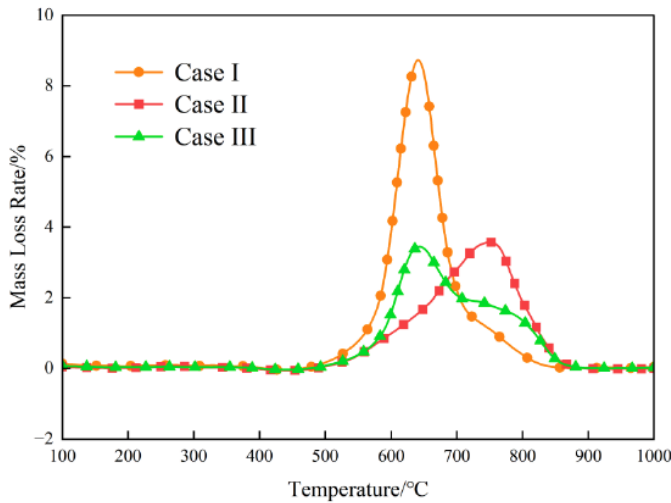


Figure 6: Fuel DTG curves.

3.2. Operating Stability of Pilot Platform

Figure 7 shows the real-time furnace temperature curves for Case I, II, and III. For Case I, the average feed rate was about $386.76 \text{ kg} \cdot \text{h}^{-1}$. Temperature of dense phase zone (T_{dep}) stabilized around 880°C , temperature of dilute phase zone (T_{dip}) was around 860°C , temperature of furnace outlet (T_{fo}) was around 850°C , and temperature of reburning section (T_{rb}) around 650°C . For Case II, the average feed rate was about $388.11 \text{ kg} \cdot \text{h}^{-1}$. T_{dep} stabilized around 870°C , T_{dip} around 860°C , T_{fo} around 850°C , and T_{rb} around 600°C . For Case III, the average feed rate was about $374.59 \text{ kg} \cdot \text{h}^{-1}$. All three temperatures (T_{dep} , T_{dip} , T_{fo}) increased over time initially, eventually stabilizing around 860°C , 840°C , and 820°C respectively, with T_{rb} around 650°C . For all three cases, the temperature distribution throughout the combustion system was uniform with small fluctuations. For Case I, temperature fluctuations at various points were within 50°C , while for Cases II and III, they were within 20°C , which are controllable ranges. Uniform temperature and small fluctuations are attributed to the strong gas–solid mixing, bed material circulation,

and loop seal return in the CFB. The benefit is that low-calorific-value fuels can be burned stably, local hot spots and slagging are reduced, and within the 90-min test duration, the system operated stably, demonstrating the operational feasibility of this technology.

3.3. Combustion Products Analysis

3.1.1. Fly Ash and Bottom Slag

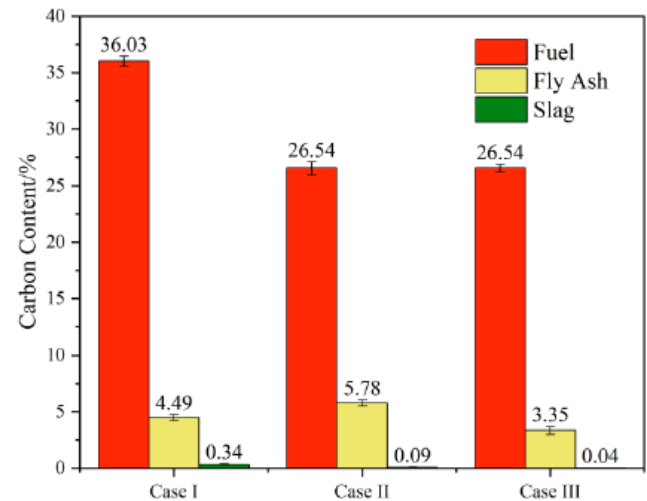


Figure 8: Carbon content of fuel, fly ash, and bottom slag.

The carbon content of the collected fly ash and bottom slag was measured; results are shown in Figure 8. The fly ash carbon content (C_{fa}) was relatively high, between 3–6%, corresponding to fly-ash carbon/ash ratios of 0.047, 0.061, and 0.035, compared with fuel carbon/ash ratios of 0.572, 0.309, and 0.316. The bottom slag carbon content (C_{si}) was extremely low (0.04–0.34%). This is because the CFB provides long particle residence time through circulation and return, and the burnout chamber allows further combustion of unburned carbon. The highly reactive CGFS residual carbon also promotes burnout of the blend. The decrease in fly ash specific surface area and pore volume is related to carbon loss, particle

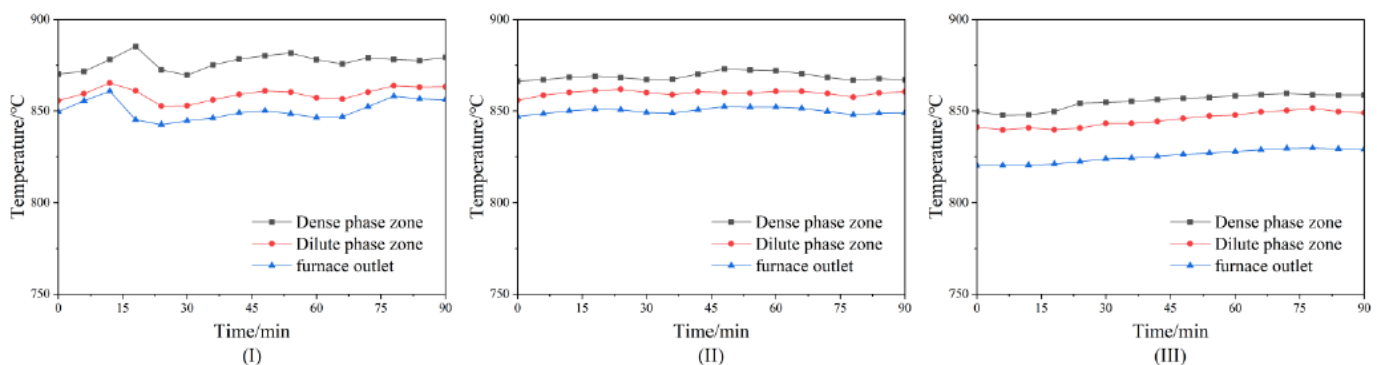


Figure 7: Real-time furnace temperature curves for Cases I, II, and III.

Table 6: Ash composition analysis of fly ash

Content/%	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O
Case I	47.12	17.12	9.48	6.23	8.02	1.91	4.21
Case II	38.12	20.24	13.89	9.61	6.50	1.48	5.81
Case III	47.42	18.23	11.06	6.47	7.75	1.53	4.54

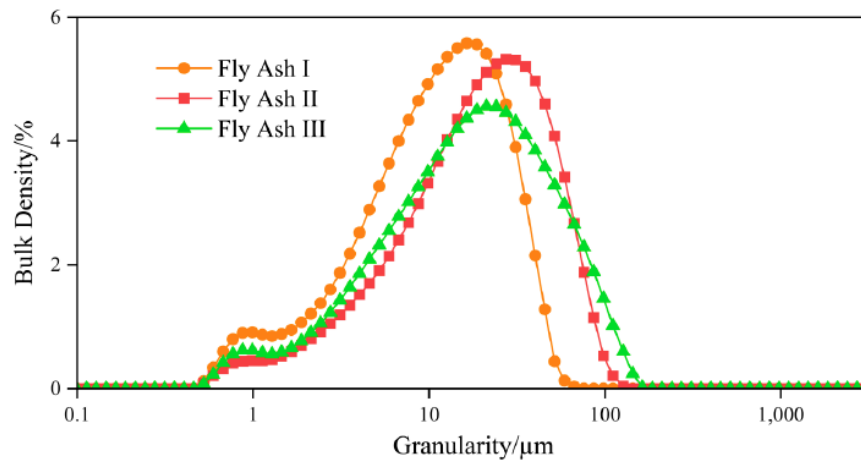
attrition, and mineral melting/aggregation. The benefit is lower unburned carbon loss, higher boiler efficiency, and fly ash that is more mineral-rich and potentially easier to utilize.

Ash composition analysis of the fly ash was performed; results are shown in Table 6. The main components of the fly ash were SiO₂ and Al₂O₃, accounting for over 60%, while the contents of CaO and Fe₂O₃ increased compared to the fuel.

Particle size data for the fly ash from the three cases were obtained using a Malvern particle size analyzer; results are shown in Figure 9. Case I fly ash had the smallest overall particle size, Case II the largest, and Case III was between the two. The particle sizes of the fly ash for all three cases were generally below 100 μm, significantly smaller than the fuel particles. The specific surface area and total pore volume of the fly ash were measured using an American Micromeritics ASAP2460 automatic surface area and porosity analyzer; results are

shown in Table 7. Compared to the fuels, the specific surface area and total pore volume of the fly ash decreased significantly. These changes are likely due to the loss of carbon during combustion in the boiler, particle size reduction due to attrition in the fluidized bed, and the loss of microporous carbon, leading to decreased particle specific surface area and total pore volume.

SEM analysis was performed on the fly ash; results are shown in Figure 10. Most boiler fly ash particles exhibited irregular shapes. Many particles appeared like broken glass shards with sharp edges and uneven surfaces. Some fly ash particles were spherical or near-spherical. This might be because during fuel combustion, various substances undergo complex physical and chemical reactions at high temperatures, generating solid particles without fixed crystal structures. Aggregation phenomena were observed among fly ash particles. In the SEM images, some larger particles were formed by the aggregation of multiple smaller particles. This aggregation might be due to electrostatic forces, van der

**Figure 9:** Fly ash particle size distribution.**Table 7:** Fly Ash Specific surface area and total pore volume

Parameter/Unit	Fly Ash I	Fly Ash II	Fly Ash III
S _p /m ² ·g ⁻¹	64.4462	11.2338	9.3179
V _p /cm ³ ·g ⁻¹	0.067433	0.018911	0.015598

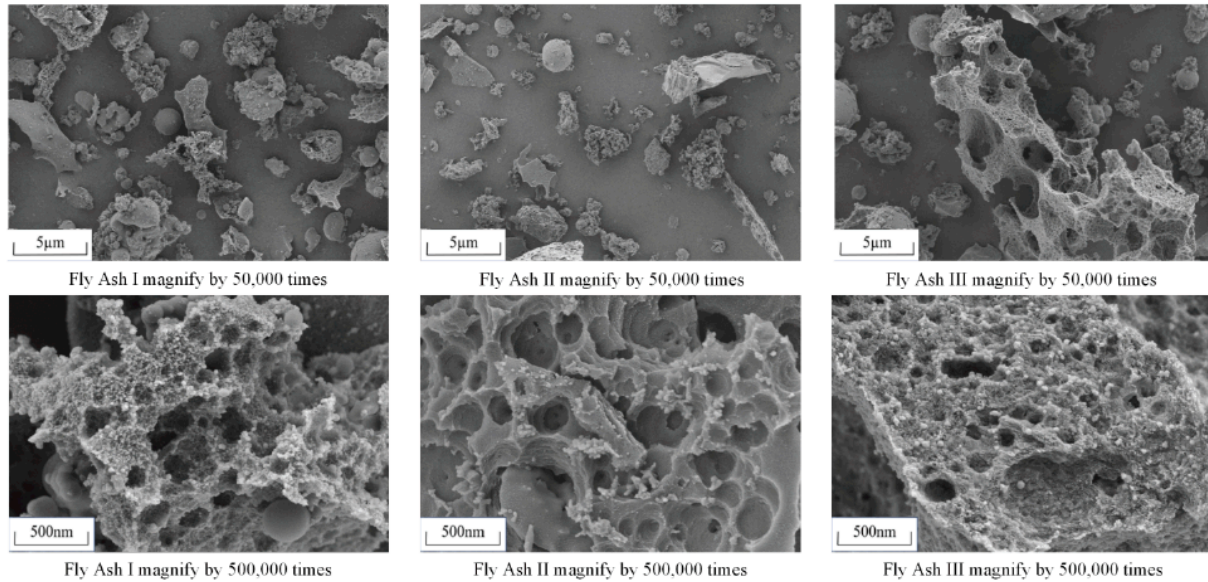


Figure 10: SEM images of fly ash.

Waals forces, or other interaction forces between particles. Many fly ash particle surfaces contained pores. The formation of these pores is related to gas escape during combustion, uneven shrinkage of material, and other factors. In SEM images, pores appear as small holes on the particle surface, with varying pore sizes. Fly ash particle surfaces exhibited various textures. Some particle surfaces showed rough textures, as if corroded. This might be due to chemical reactions between the particle surface and gases in the surrounding environment during combustion, leading to dissolution or deposition of surface material. Other particle surfaces were relatively smooth, possibly due to their more homogeneous composition and less external interference during formation.

3.3.2. Gas Pollutant Emission

Flue gas composition and concentration were monitored on-site using a HORIBA-PG-300 compact and lightweight

infrared gas analyzer, with recordings every 10 minutes. The real-time emission characteristics of NO_x , SO_2 , and CO are shown in Figure 11. The average concentrations and the relevant fuel properties are summarized in Table 8. Table 9 summarizes the emission limits specified in the Ningxia local standard DB 64/1996–2024, Emission Standard of Air Pollutants for Coal-Fired Power Plants, together with the pollutant concentrations for the three cases normalized to a 6% O_2 basis using the measured O_2 concentrations (NO_x expressed as NO_2); the measured average flue-gas O_2 concentrations were 6.895%, 6.5%, and 7.534% for Cases I, II, and III, respectively.

NO_x generated from coal-based fuel combustion mainly includes fuel- NO_x , thermal- NO_x , and prompt- NO_x [26]. In this study, the furnace temperature was generally in the range of 800–900 °C, therefore, fuel- NO_x was the dominant source, while thermal- NO_x was limited. Fuel- NO_x formation includes the release and oxidation of

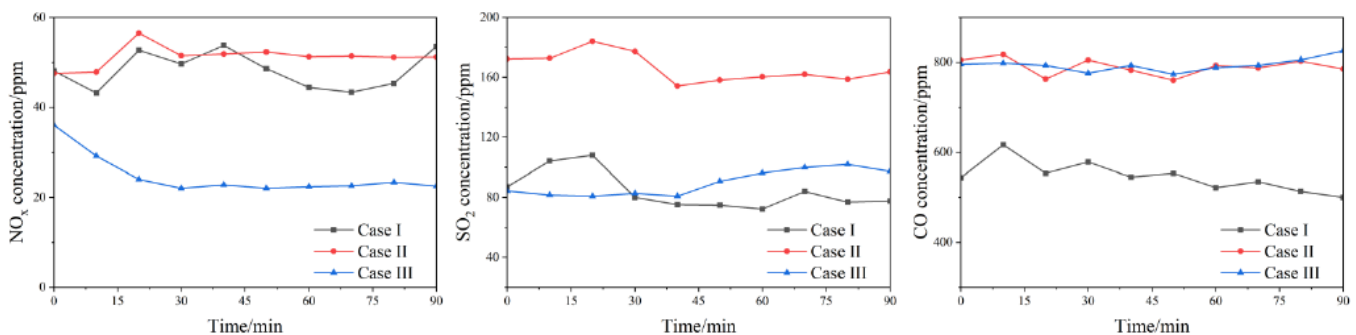


Figure 11: NO_x , SO_2 , CO emission characteristics.

Table 8: Pollutant emissions and fuel properties for the three cases

Case	Fuel N	Fuel S	Average NO _x	Average SO ₂	Average CO
	(wt.%, ad)	(wt.%, ad)	(ppm)	(ppm)	(ppm)
I	0.20	0.24	48.2	84.0	556
II	0.22	0.52	51.2	166.3	809
III	0.22	0.30	24.7	89.6	794

Table 9: DB 64/1996–2024 emission limits and O₂-normalized pollutant concentrations for the three cases

Pollutant	Unit	Limit	Case I	Case II	Case II	Compliance
SO ₂	mg/Nm ³ @6% O ₂	≤35	255.5	492.0	285.4	All exceed
NO _x as NO ₂	mg/Nm ³ @6% O ₂	≤50	105.3	108.8	56.5	All exceed
CO	mg/Nm ³ @6% O ₂	/	739.7	1047.0	1106.4	/

*All values are on a dry, standard-state basis and normalized to 6% O₂; NO_x is expressed as NO₂; CO has no limit in DB 64/1996–2024 and is reported for reference only.

volatile nitrogen and the oxidation of char nitrogen [27]. However, the fuels used in this study had extremely low volatile matter ($V_{ad} = 0.96\text{--}1.78\%$ for the three tested cases; $0.57\text{--}3.42\%$ for the raw fuels), so the release of volatile nitrogen was very limited. Consequently, fuel-NO_x formation mainly originated from the oxidation of char nitrogen, and the NO_x emission was dominated by the char combustion stage rather than the volatile combustion stage. Many factors affect the formation of fuel-NO_x, such as oxygen concentration and temperature [28], and the conversion of fuel nitrogen to NO_x is also influenced by local O₂ concentration and char concentration. In addition, NO can be reduced by char and CO to N₂, which is prone to occur in a reducing atmosphere [29].

For Case I, the average NO_x concentration was 48.2 ppm. For Case II, it was 51.2 ppm, the highest among the three cases. For Case III, the instantaneous NO_x concentration was relatively high at the beginning, then gradually decreased and stabilized, with an average of 24.68 ppm, the lowest among the three cases. Case III had a lower furnace temperature (approximately 860/840/820°C in the dense-phase/dilute-phase/outlet zones). Because thermal-NO_x is negligible under this 800–900°C CFB condition, the lower NO_x in Case III is mainly attributed to the suppression of char-N oxidation at the lower temperature and to enhanced NO reduction by char/CO in the reducing zone. Case II showed slightly higher NO_x than Case I, although the difference was small. This may be related to its slightly higher fuel nitrogen content, more concentrated combustion, and the relatively low reburning-zone temperature (about 600 °C), which may have weakened NO_x reduction in the reburning-zone [29].

Overall, the raw NO_x concentrations in all three cases were 20–60 ppm, which is mainly attributed to the low fuel nitrogen content, the extremely low volatile matter, and the low-to-medium combustion temperature in the CFB. Because thermal-NO_x is negligible at 800–900°C, fuel-NO_x—predominantly from char-N oxidation—is the controlling source. After normalization to 6% O₂, however, NO_x (as NO₂) reached 105.3, 108.8, and 56.5 mg/Nm³ for Cases I–III, all exceeding the 50 mg/Nm³ limit of DB 64/1996–2024. Therefore, these values should be regarded as uncontrolled baseline emissions rather than compliant low emissions. In practical industrial applications, low-NO_x combustion technologies such as air staging and fuel staging can reduce the initial NO_x formation, while SNCR or SCR is required to bring the normalized NO_x concentration below the 50 mg/Nm³ limit. The benefit is that the relatively low raw NO_x concentration reduces the reagent consumption and operating cost of the downstream DeNO_x unit, while full compliance still depends on the combined use of staged combustion and SNCR/SCR.

Sulfur in coal-based fuels exists in inorganic and organic forms, with some fuels containing a small amount of elemental sulfur [30]. Inorganic sulfur mainly occurs as sulfides and sulfates, while organic sulfur exists in functional groups such as mercaptans, thioethers, and thiophenes. During combustion, organic sulfur, free sulfur, and sulfur in pyrite can undergo combustion reactions [31]. Sulfates in inorganic sulfur are non-combustible and difficult to decompose, but they can decompose under high-temperature conditions. The release and conversion of sulfur are influenced by sulfur content, occurrence mode, combustion temperature, local oxygen

concentration, residence time, and ash composition, especially the CaO content. CaO can capture SO_2 through sulfation to form CaSO_4 , but this reaction is temperature-sensitive; at excessively high temperatures, the sulfation products may decompose, reducing the sulfur-retention effect [32].

For Case I, the average raw SO_2 concentration was 84 ppm. For Case II, it was 166.3 ppm, the highest among the three cases. For Case III, it was 89.6 ppm, and it exhibited the smallest fluctuation amplitude among the three cases. Case II had the highest sulfur content in the ultimate analysis (0.52 wt.%, ad), and its raw flue-gas SO_2 concentration was correspondingly the highest. The relatively high temperature in Case II also promoted the rapid release and oxidation of sulfur, and the high-temperature environment may have caused part of the sulfur-containing ash products to decompose again into SO_2 [32]. Case III had a lower sulfur content (0.30 wt.%, ad) and a lower furnace temperature, and the CaO and Fe_2O_3 in the ash may have played a positive role in sulfur retention, resulting in a relatively low and stable raw SO_2 concentration. Case I had the lowest sulfur content (0.24 wt.%, ad), so its raw SO_2 concentration was also relatively low. However, after normalization to 6% O_2 , the SO_2 concentrations were 255.5, 492.0, and 285.4 mg/Nm^3 for Cases I–III, respectively, all far exceeding the 35 mg/Nm^3 limit of DB 64/1996–2024. Therefore, these values should be regarded as uncontrolled baseline emissions rather than compliant low emissions. In practical industrial applications, in-furnace limestone injection or wet flue gas desulfurization is required to reduce the normalized SO_2 concentration below 35 mg/Nm^3 . The benefit is that the relatively low raw SO_2 concentration reduces desulfurization reagent consumption and corrosion risk in the tail flue, while full compliance still depends on the FGD system [30, 31].

CO is an intermediate product of the incomplete combustion of carbon-containing substances. Incomplete combustion tends to produce CO. Its concentration in flue gas is mainly related to combustion temperature, local oxygen concentration, fuel reactivity, particle size, gas–solid mixing, and fuel residence time [33]. Higher temperature, sufficient oxygen, and longer residence time favor the oxidation of CO to CO_2 , whereas dense and low-reactivity carbon, poor mixing, and local oxygen deficiency lead to CO accumulation [34]. In addition, CO can participate in NO reduction [35], so a certain CO concentration in reducing zones may be beneficial for NO_x control, but excessive CO indicates incomplete combustion and reduces boiler efficiency.

In Case I, the average raw CO concentration was 556 ppm. In Cases II and III, the average raw CO concentrations were 809 ppm and 794 ppm, respectively. The CO concentration in Case I was relatively lower than those in Cases II and III. Case I used pure CGFS, whose residual carbon has a well-developed pore structure and high reactivity, and the combustion temperature was relatively higher, which favored the complete oxidation of CO [33]. Cases II and III were blended with CCDA, in which the fixed carbon has a dense, anthracite-like structure, poor reactivity, and is difficult to ignite and burn out; this may lead to local incomplete combustion and higher CO emission. Case III had slightly lower CO than Case II because the highly reactive CGFS improved the ignition and burnout of the ternary blend, consistent with its lower E_a and higher combustion efficiency. After normalization to 6% O_2 , the CO concentrations were 739.7, 1047.0, and 1106.4 mg/Nm^3 for Cases I–III, respectively. It should be noted that DB 64/1996–2024 does not specify a CO limit; therefore, these CO values are reported for reference and are not used for compliance judgment. The raw CO concentrations of 556–809 ppm indicate that chemical incomplete combustion was not negligible, although the calculated chemical incomplete combustion loss q_3 remained small. In actual industrial boilers with greater furnace height and longer fuel residence time, CO emissions can be further reduced by optimizing secondary air, burnout air, and combustion temperature. The benefit of lower CO is lower chemical incomplete combustion loss and higher boiler efficiency; although Cases II and III had slightly higher CO, their combustion efficiencies still exceeded 83%, indicating acceptable overall combustion performance under pilot-scale conditions, while further CO reduction is expected in full-scale boilers.

The raw flue-gas concentrations of the three cases were NO_x 20–60 ppm, SO_2 70–180 ppm, and CO 500–850 ppm. These raw concentrations are mainly attributed to the low nitrogen and sulfur contents of the fuels, the low-to-medium CFB combustion temperature, staged combustion, strong gas–solid mixing, and long residence time. However, after normalization to 6% O_2 , SO_2 reached 255.5–492.0 mg/Nm^3 and NO_x (as NO_2) reached 56.5–108.8 mg/Nm^3 , all exceeding the DB 64/1996–2024 limits of 35 and 50 mg/Nm^3 , respectively. Therefore, these values should be regarded as uncontrolled baseline emissions rather than compliant low emissions. Among the three cases, Case III achieved the best balance between relatively low raw NO_x emission (24.7 ppm; 56.5 mg/Nm^3 as NO_2 at 6% O_2) and high combustion efficiency, although its CO was slightly higher than that of Case I and its normalized NO_x still slightly

exceeded the 50 mg/Nm³ limit. In industrial applications, the combination of CFB co-firing with SNCR/SCR, in-furnace limestone injection, and optimized air staging is required to bring SO₂ and NO_x below the DB 64/1996–2024 limits; these measures are not merely optional further reductions. The overall benefit is that CFB co-firing can simultaneously achieve large-scale resource utilization of CGS and CCDA and provide a basis for low-emission operation after appropriate flue-gas cleaning, offering a promising route for the clean and low-carbon utilization of coal-based solid wastes.

■ 3.3.3. Combustion Efficiency

Combustion efficiency is a crucial factor determining boiler efficiency. In this study, the chemical incomplete combustion loss of gas (q_3) was small and is therefore not considered as a controlling factor in the following analysis. The combustion efficiency (η_c) was mainly determined by the unburned carbon loss of fly ash and bottom slag (q_4), as shown in Eqs. (1)–(3). The q_4 loss depends on the ash fraction and carbon content of the fly ash and bottom slag [14,15]. After obtaining the bottom slag fraction (α_{sl}), bottom slag carbon content (C_{sl}), fly ash fraction (α_{fa}), and fly ash carbon content (C_{fa}), q_4 and η_c were calculated. The results are shown in Table 10.

For Case I, the combustion efficiency reached 92.53%, the highest among the three cases. This is mainly because Case I used pure CGFS, whose residual carbon has a well-developed pore structure and large specific surface area [6, 25]. These characteristics promote oxygen diffusion into the particle interior, accelerate char oxidation, and improve burnout. The fly ash carbon content was 4.49%, and the bottom slag carbon content was only 0.34%, so both q_{4fa} and q_{4sl} were small. The benefit is high boiler efficiency, low unburned carbon loss, and fly ash with relatively low carbon content, which is favorable for subsequent utilization.

For Case II, the combustion efficiency was 83.86%, the lowest among the three cases. This can be attributed to several factors. First, Case II was a binary blend of CGCS and CCDA. CGCS has a low calorific value and

poor combustion performance [7, 8], while CCDA has a dense, anthracite-like carbon structure with low reactivity, making ignition and burnout difficult [23]. Second, the blended fuel had the largest mean particle size (212.17 μm) and the lowest specific surface area and total pore volume, which increased the mass-transfer limitation of oxygen and hindered char oxidation. Third, the fly ash fraction in Case II was as high as about 90%, and the fly ash carbon content was 5.78%, resulting in a relatively large q_{4fa} , which was the dominant unburned carbon loss. Fourth, the reburning-zone temperature in Case II was about 600°C, lower than that in Cases I and III (about 650°C), which was unfavorable for further burnout of unburned carbon in the burnout chamber. Although the combustion efficiency of Case II was the lowest, it still exceeded 80%, demonstrating that even a difficult-to-burn CGCS + CCDA blend can be stably combusted in a CFB. The benefit is that this provides a feasible route for consuming low-calorific-value CGCS and difficult-to-burn CCDA, although further optimization of the burnout air and reburning temperature is needed to reduce C_{fa}.

For Case III, the combustion efficiency reached 91.21%, close to that of Case I and much higher than that of Case II. This may suggest a possible synergistic effect in the ternary blend. The reasons are as follows. First, the highly reactive residual carbon in CGFS promotes initial ignition and subsequent burnout of the blend [6, 25]. Second, CCDA supplies high-carbon fuel and heat, compensating for the low calorific value of CGCS [23]. Third, minerals such as CaO and Fe₂O₃ in the ash may catalyze char oxidation and oxygen transfer, which is consistent with the lowest E_a of Case III (95.8 kJ·mol⁻¹) [26]. The benefit is that the ternary blending strategy achieves a good balance among stable combustion, high combustion efficiency, and simultaneous consumption of CGFS, CGCS, and CCDA.

Overall, the combustion efficiencies of the three cases were 92.53%, 83.86%, and 91.21%, respectively, all exceeding 80%. Most of the ash was discharged as fly ash, with fly ash fractions exceeding 90% in the tested

Table 10: Combustion Efficiency under Various Test Cases

Case	Feed Rate (kg·h ⁻¹)	α_{sl} (%)	α_{fa} (%)	q_{4fa} (%)	q_{4sl} (%)	q_3 (%)	η_c (%)
I	386.76	5	95	7.18	0.03	0.26	92.53
II	388.11	10	90	15.78	0.03	0.35	83.86
III	374.59	8	92	8.43	0.01	0.35	91.21

cases, so the primary loss was unburned carbon in the fly ash. The furnace temperature, reburning-zone temperature, fuel reactivity, particle size, pore structure, and ash composition jointly affected η_c . In actual industrial boilers, the furnace height is greater and the fuel residence time is longer, so C_{fa} can be further reduced by optimizing secondary air, burnout air, and combustion temperature, thereby further increasing η_c . The overall benefit is that CFB co-firing can achieve large-scale resource utilization of CGS and CCDA while maintaining high combustion efficiency and low unburned carbon loss, providing basic data for industrial demonstration.

■ 3.3.4. Preliminary Techno-Economic, CO₂ and Ash Mineralization Analysis

To evaluate the engineering potential of circulating fluidized bed (CFB) co-firing of coal-based solid wastes, a simplified annual-scale techno-economic analysis (TEA) and CO₂ estimate were carried out based on Case III. The assumed annual consumption of ternary solid waste is 400,000 t (34% CGFS, 51% CGCS, and 15% CCDA), with 8,000 operating hours per year. The as-received net calorific value of the Case III fuel is about 1,783 kcal·kg⁻¹ (Table 11), the combustion efficiency is 91.21% (Table 10), the boiler thermal efficiency is taken as 80%–85%, and the steam enthalpy is 2.8 GJ·t⁻¹. Accordingly, the annual heat input is about 2.99×10⁶ GJ, equivalent to an annual standard coal saving of about 1.02×10⁵ tce based on 29.3076 GJ·tce⁻¹. Based on effective heat release, the equivalent standard coal saving is about 9.3×10⁴ tce·a⁻¹, and the corresponding steam output is about 7.8×10⁵–8.3×10⁵ t·a⁻¹. These results indicate that the CFB co-firing route can consume large amounts of CGS and CCDA while providing substantial steam supply capacity, with the potential to replace part of coal-fired boilers.

For CO₂, the air-dried basis carbon content of the Case III fuel is 22.54%. Converted using the as-received moisture content of 16.40%, the as-received carbon content is about 19.05%. The annual carbon input is about 7.62×10⁴ t. After deducting about 7.45×10³ t of unburned carbon in fly ash and bottom slag, the oxidized carbon is about 6.88×10⁴ t, corresponding to direct CO₂ emissions of about 2.52×10⁵ t·a⁻¹. Based on equal-heat replacement of standard coal, the avoided coal-fired CO₂ emissions are about 2.71×10⁵ t·a⁻¹ (using 2.66 t CO₂·tce⁻¹). When the carbon in the solid wastes is also counted, the net reduction is about 1.9×10⁴ t CO₂·a⁻¹. It should be noted that the residual carbon in CGS and CCDA is still

fossil carbon, and the net climate benefit depends on the baseline disposal scenario, the carbon intensity of the substituted energy, and CO₂ sequestration by ash mineralization; this should be further verified through life-cycle assessment (LCA).

The annual ash generation is about 2.41×10⁵ t (as-received ash content about 60.35%), including about 2.22×10⁵ t of fly ash and about 1.9×10⁴ t of bottom slag. In Case III, SiO₂ and Al₂O₃ in the fly ash total about 65.65%, CaO is about 6.47%, and MgO is about 7.75%. The fly ash carbon content is only 3.35%, and the bottom slag carbon content is 0.04%. The ash therefore has potential for use in mine backfilling, roadbed materials, building-material admixtures, lightweight aggregates, and CO₂ mineralization feedstock. Based on complete carbonation of CaO and MgO in the fly ash, the theoretical CO₂ sequestration potential is about 3.0×10⁴ t CO₂·a⁻¹; a conservative estimate assuming 30% reactivity gives about 0.9×10⁴ t CO₂·a⁻¹. The mineralization products are relatively stable CaCO₃/MgCO₃, which can be used as backfill aggregate or building-material feedstock, forming an integrated chain of “solid waste consumption–steam production–CO₂ mineralization.” However, heavy-metal leaching toxicity, radioactivity, and long-term stability tests have not yet been carried out in this study. Before engineering application, leaching data for As, Cd, Cr, Pb, Hg, etc. should be supplemented according to GB 5085.3 and GB 18599. If these requirements are not met, stabilization/solidification should be applied before reuse or disposal.

In the preliminary TEA, based on a steam price of CNY 120–180·t⁻¹, a solid waste disposal fee of CNY 30–80·t⁻¹, and ash utilization at CNY 20–60·t⁻¹, the annual revenue is about CNY 110–200 million. The operating costs, including pretreatment/drying, fans, desulfurization and denitrification, ash handling, and labor/maintenance, are about CNY 32–48 million·a⁻¹. After considering environmental upgrading, depreciation, and financial costs, the static payback period is roughly 4–7 years; if the steam price and solid waste disposal fee are at the high end of the ranges, it can be shortened to 3–4 years. CGFS has a moisture content of about 30%, and drying/pretreatment and flue gas cleaning are the main cost-sensitive items. When the steam price is below CNY 100·t⁻¹ or the solid waste disposal fee is below CNY 20·t⁻¹, the project would require policy subsidies or carbon revenue support. In terms of employment, based on scheme-level estimates for similar solid waste/biomass CFB steam projects, a 400,000 t·a⁻¹ ternary solid waste co-firing project can directly provide about 60–100 jobs

Table 11: Preliminary TEA and CO₂ estimates for Case III at an annual solid waste consumption of 400,000 t

Item	Unit	Value/range	Note
Annual consumption of ternary solid waste	t·a ⁻¹	400,000	34% CGFS + 51% CGCS + 15% CCDA
As-received net calorific value	kcal·kg ⁻¹	1,783	Table 1
Annual heat input	GJ·a ⁻¹	2.99×10 ⁶	Converted based on 1,783 kcal·kg ⁻¹
Standard coal equivalent	tce·a ⁻¹	1.02×10 ⁵	29.3076 GJ·tce ⁻¹
Standard coal equivalent of effective heat	tce·a ⁻¹	9.3×10 ⁴	Based on $\eta_c = 91.21\%$
Steam output	t·a ⁻¹	7.8×10 ⁵ –8.3×10 ⁵	Boiler efficiency 80%–85%
Annual ash generation	t·a ⁻¹	2.41×10 ⁵	As-received ash content about 60.35%
Fly ash/bottom slag	t·a ⁻¹	2.22×10 ⁵ /1.9×10 ⁴	$\alpha_{fb} = 92\%$, $\alpha_{sl} = 8\%$
Direct CO ₂ emissions	t·a ⁻¹	2.52×10 ⁵	After deducting unburned carbon
CO ₂ avoided by replacing standard coal	t·a ⁻¹	2.71×10 ⁵	2.66 t CO ₂ ·tce ⁻¹
Net reduction (including waste carbon)	t·a ⁻¹	~1.9×10 ⁴	Project emissions vs coal baseline
CO ₂ sequestration potential by ash mineralization	t·a ⁻¹	0.9×10 ⁴ –3.0×10 ⁴	30%–100% reactivity
Annual revenue	CNY million·a ⁻¹	110–200	Steam + disposal fee + ash utilization
Static payback period	a	4–7	Scheme-level estimate

and indirectly drive about 150–250 jobs in material collection and transport, pretreatment, ash utilization, and logistics, totaling about 210–350 people. However, the employment scale is affected by the automation level and industrial chain support and needs further assessment in the industrial demonstration stage. This estimate is only a scheme-level order-of-magnitude judgment; detailed TEA still needs to be carried out based on the whole-plant heat balance, equipment selection, local energy prices, and financing conditions.

In summary, CFB co-firing of CGS and CCDA can convert low-value coal-based solid wastes into steam and direct ash toward CO₂ mineralization and building-material utilization, improving resource recycling efficiency and supporting SDG 7 (clean energy), SDG 8 (decent work and economic growth), SDG 9 (industry, innovation and infrastructure), SDG 11 (sustainable cities), SDG 12 (responsible consumption and production), and SDG 13 (climate action). However, net emission reduction and ash environmental safety are still affected by the baseline scenario, mineralization reactivity, and leaching characteristics. It is recommended that LCA and ash environmental risk assessment be carried out simultaneously in the industrial demonstration.

■ 4. CONCLUSIONS

To achieve the resource utilization of CGS and CCDA, this paper proposes a novel circulating fluidized bed

combustion technology for co-firing coal CGS with CCDA. In this study, a 2 MWth pilot-scale test was conducted under three fuel cases to evaluate operational feasibility, ash characteristics, gaseous pollutant emissions, and combustion efficiency. The main conclusions are as follows:

(1) Thermogravimetric analysis results showed that the ignition temperatures for the fuels in Case I, Case II, and Case III were 595.7°C, 637.6°C, and 594.8°C, respectively, and the burnout temperatures were 687.8°C, 802.5°C, and 807.6°C, respectively. The apparent activation energies of the fuels, calculated by the Coats-Redfern method, were 157.7 kJ·mol⁻¹, 115.1 kJ·mol⁻¹, and 95.8 kJ·mol⁻¹ for the three cases, respectively.

(2) During the pilot-scale tests for all three cases, feeding was smooth and stable, the circulation loop was unobstructed, and the temperature distribution throughout the combustion system was uniform with minor fluctuations. For Case I, temperature fluctuations at various points were within 50°C, while for Cases II and III, they were within 20°C, which are controllable ranges. The operating time for each case exceeded 90 minutes, demonstrating operational feasibility.

(3) Analysis of the fuels and boiler fly ash for the three cases showed a significant reduction in the carbon content of the fly ash compared to the fuels, the corresponding fly-ash carbon/ash ratios were 0.047,

0.061, and 0.035. The particle size, specific surface area, and total pore volume decreased. The main components of the fly ash were SiO_2 and Al_2O_3 , collectively accounting for over 60%, while the contents of CaO and Fe_2O_3 increased compared to the fuels.

(4) Measurements of gaseous pollutant emissions for the three cases gave the following raw flue-gas concentrations: NO_x 20–60 ppm, SO_2 70–180 ppm, and CO 500–850 ppm. After normalization to 6% O_2 , however, SO_2 was 255.5–492.0 mg/Nm^3 and NO_x (as NO_2) was 56.5–108.8 mg/Nm^3 , all exceeding the limits specified in the relevant standards. Therefore, these values represent pre-control baseline emissions rather than compliant low emissions. In practical industrial operations, in-furnace limestone injection or wet FGD and SNCR/SCR are required to reduce SO_2 and NO_x below the regulatory limits; with these measures, the emissions can be further reduced to meet ultra-low emission requirements.

(5) Combustion efficiency analysis considered unburned carbon losses in fly ash and bottom slag. For all three cases, most of the ash was discharged as fly ash, with fly ash fractions exceeding 90%. The carbon content in the fly ash generally ranged from 3% to 6%, while the fraction and carbon content of the bottom slag were minimal. Thus, the primary loss was unburned carbon in the fly ash. The combustion efficiencies (η_c) for the three cases were 92.53%, 83.86%, and 91.21%, respectively, all exceeding 80%, indicating good combustion performance.

(6) Based on stated assumptions, preliminary estimates for Case III ($400,000 \text{ t}\cdot\text{a}^{-1}$, $8,000 \text{ h}\cdot\text{a}^{-1}$) indicate $\sim 9.3 \times 10^4 \text{ tce}\cdot\text{a}^{-1}$ standard coal saved, $7.8\text{--}8.3 \times 10^5 \text{ t}\cdot\text{a}^{-1}$ steam, $2.52 \times 10^5 \text{ t}\cdot\text{a}^{-1}$ direct CO_2 , $2.71 \times 10^5 \text{ t}\cdot\text{a}^{-1}$ avoided CO_2 , and $\sim 1.9 \times 10^4 \text{ t}\cdot\text{a}^{-1}$ net reduction. Estimated ash ($\sim 2.41 \times 10^5 \text{ t}\cdot\text{a}^{-1}$) may support building materials and CO_2 mineralization ($0.9\text{--}3.0 \times 10^4 \text{ t}\cdot\text{a}^{-1}$). Scheme-level TEA suggests CNY 110–200 million $\cdot\text{a}^{-1}$ revenue, 4–7-year payback, and 210–350 jobs, supporting SDGs 7–13.

■ CONFLICT OF INTEREST

The authors declare no conflict of interest.

■ FUNDING

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■ DATA AVAILABILITY

Data will be made available on request.

■ NOMENCLATURE

A	ash content; pre-exponential factor(%)
FC	fixed carbon(%)
V	volatile matter(%)
M	moisture matter(%)
$Q_{net,ar}$	net calorific value as received($\text{kcal}\cdot\text{kg}^{-1}$)
q_3	uncompletely combustion loss of gas (%)
q_4	uncompletely combustion loss of carbon (%)
V_f	dry flue gas volume per unit fuel mass($\text{m}^3\cdot\text{kg}^{-1}$)
q_{4fa}	fly ash incomplete-combustion loss (%)
q_{4sl}	slag incomplete-combustion loss (%)
α_{fa}	fly ash mass fraction of ash (%)
C_{fa}	carbon content in fly ash (wt %)
α_{sl}	slag mass fraction (%)
C_{sl}	carbon content in slag (wt %)
η_c	combustion efficiency (%)
E_a	Apparent activation energy($\text{kcal}\cdot\text{mol}^{-1}$)
A	Pre-exponential factor(min^{-1})
T_{dep}	average temperature in dense phase($^{\circ}\text{C}$)
T_{dip}	average temperature in dilute phase($^{\circ}\text{C}$)
T_{fo}	average temperature in furnace outlet($^{\circ}\text{C}$)
T_{rb}	average temperature in reburning-zone($^{\circ}\text{C}$)
T_{dip}	average temperature in dilute phase($^{\circ}\text{C}$)
V_p	total pore volume ($\text{cm}^3\cdot\text{g}^{-1}$)
CGS	coal gasification slag
CGFS	coal gasification fine slag
CGCS	coal gasification coarse slag
CCDA	coal coking dedusting ash

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