New Strategy toward Household Coal Combustion by Remarkably Reducing SO₂ Emission

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ABSTRACT: A large amount of sulfur dioxide (SO₂) will be released during rural household coal combustion, causing serious environmental pollution. Therefore, it is very urgent to develop a clean and efficient fuel to substitute rural household coal controlling SO₂ emission. In this paper, a new strategy toward scattered coal combustion with remarkably reducing SO₂ emission was proposed. Coal and compound additive of Al₂O₃ and CaCO₃ were blended and then copyrolysis at 1050 °C was performed to produce clean coke. First, the sulfur content of clean coke was reduced, meanwhile, generating sulfur fixation precursor during pyrolysis. Then, clean coke is used for efficient sulfur fixation during the subsequent combustion process to reduce SO₂ emissions. The effects of combustion temperature, Al/S molar ratio, and the mechanism of sulfur retention during clean coke combustion were studied in the tube furnace and muffler furnace. The mechanism can be attributed to the following reason: (a) CaS produced during pyrolysis and CaO decomposed by complex additives were oxidized during combustion, and CaO captured the SO₂ released from clean coke combustion, which formed CaSO₄. (b) CaSO₄ reacts with Al₂O₃ to produce calcium sulfoaluminate at high temperatures, which improves the sulfur fixation efficiency of clean coke combustion at high temperatures. In a word, this new strategy can greatly reduce the emission of SO₂, thus helping to solve rural household coal pollution problems.

1. INTRODUCTION

Coal is the most important primary energy, and it will continue to be the dominant energy source for China in the near future. According to statistics, the consumption of coal reaches 490 million tons, and the consumption of scattered coal is nearly 7.55 billion tons, of which 234 million tons are used for the fuel combustion of the domestic stove in 2017.1–3 However, rural household coal mostly leads to disorganized low-altitude emissions, dispersed combustion, and incomplete combustion. Moreover, the lack of desulfurization and denitrification equipment results in the discharge of flue gas with high concentrations of SO₂ and NOₓ. The emission intensity of SO₂ from residential coal burning is at least 3–8 times that of coal-fired power plants.4 How to solve the problem of SO₂ emission from civil scattered combustion is worth pondering.

Ca-based sorbents are the well-known and commonly used sorbents for SO₂ removal from combustion gases because of their wide availability, low price, and high efficiency.5–10 Guan,11 carried out combustion experiments of coal with three kinds of calcium-based sulfur fixation agents (CaO, Ca(OH)₂, and CaCO₃) and found that Ca(OH)₂ had a better effect on sulfur fixation and CaCO₃ promoted the release of SO₂ at low temperatures. The CaCO₃/CaO solid sorbent particle size had a significant effect on SO₂ capture, and mixed solid sorbent had higher capture efficiency than the conventional pure solid sorbent.12 However, the SO₂ emission increases sharply when the combustion temperature was above 1100 °C. This is due to the thermal decomposition of the conventional sulfur-fixation product CaSO₄ above 1200 °C during coal combustion.13 Therefore, how to improve the sulfur fixation efficiency of CaSO₄ at high temperatures or how to inhibit CaSO₄ decomposition is key to solve this problem.

The results show that the 3CaO·3Al₂O₃·3CaSO₄ complex can be formed by adding Al₂O₃, which covers or wraps the surface of the CaSO₄ crystal, so that it can inhibit the decomposition of CaSO₄ and improve the sulfur fixation effect.14–16 Blast furnace sludge (BFS) exhibits a strong sulfur-fixing ability because of the large amount of metal oxides, such as Fe₂O₃, CaO, SiO₂, and Al₂O₃, that it contains. The results indicated that BFS, as a sulfur-fixing agent, is cheap and highly efficient in controlling SO₂ emissions during coal combustion processes.17 Al₂O₃ additive can obviously increase the sulfur-fixation efficiency of the biomass briquette during the combustion, and is also the reason why the efficiency increase was forming a kind of a stable high temperature phase, that is calcium sulfoaluminate (3CaO·3Al₂O₃·3CaSO₄). The C₃A₃S

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stemming from the cement industry also was discovered as the sulfur-fixation phase during the combustion of coal and researched by the researchers of desulfurization to measure the optimum ratio and the formation temperature.\textsuperscript{18−20} Therefore, considering the C\textsubscript{4}A\textsubscript{3}S as the high temperature sulfur-fixation phase during coal combustion is feasible and significantly improves the sulfur-fixation efficiency in coal combustion.

In this paper, a new strategy toward scattered coal combustion with remarkably reducing SO\textsubscript{2} emission was proposed. The flow chart is shown in Figure 1. Al\textsubscript{2}O\textsubscript{3} and CaCO\textsubscript{3} composite additives are first added into the coal pyrolysis process in advance. Then, clean coke is obtained by high-temperature pyrolysis, which reduces the sulfur content in the clean coke and forms the sulfur fixation precursor. The sulfur fixation precursor is converted to the high temperature sulfur-fixation phase C\textsubscript{4}A\textsubscript{3}S during combustion. It can greatly improve the sulfur-fixation efficiency of clean coke during the combustion of high temperatures above 1200 °C. X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD) were used to investigate the sulfur transformation in the coal, coke, and coal ash during coal pyrolysis and combustion. Thermogravimetric analysis−mass spectrometry (TGA−MS) was used to simulate the process of combustion of clean coke so as to investigate the mechanism of sulfur-fixation in combustion.

### 2. RESULTS AND DISCUSSION

#### 2.1. Study on SO\textsubscript{2} Emission Characteristics of Coal, Coke, and Clean Coke.

In this study, the thermal decomposition of raw coal, coke, coke-Ca, and coke-Ca-3%Al was analyzed at a heating rate of 10 °C/min in the air atmosphere. The derivative mass loss DTG and TG are shown in Figure 2. From the DTG curves for raw coal, it can be observed that the coal sample first experienced the weight gain process of physical adsorption and chemical adsorption at the initial stage of coal oxidation. It can be seen from the curve that the TG curve shows the first peak at 85.92 °C, and the sample quality is 97.85% of the initial mass. Subsequently, because of the reaction of the coal sample with oxygen to produce CO, CO\textsubscript{2}, SO\textsubscript{2}, and other gases,\textsuperscript{21} gas evolution and the desorption amount gradually increased, and the coal sample began to lose weight slowly. At 509.15 °C, the coal sample weight loss rate reached a maximum of 13.25%/min. When the temperature reaches to 604.41 °C, the combustible material of the sample is almost burned out, and the TG curve gradually approaches a straight line. The residual mass of the sample at this time was 15.49% of the initial mass. However, there is only one peak of coke at 632.92 °C.

As shown in Figure 2a,b, it can be seen that the TG/DTG curves of coke-Ca and coke-Ca-3%Al have similar trends, but the values corresponding to the characteristic temperature points and the degree of weightlessness are different. For the coke-Ca, the first peak in the temperature zone at around 507.26−819.31 °C for coke-Ca could be due to the release of CO\textsubscript{2} from the coke combustion. The second peak at 1250 °C observed for coke-Al was due to the decomposition of CaSO\textsubscript{4}. There is also a small peak at 701.55 °C. It can be seen that there are four obvious peaks in coke-Ca-3%Al, and the peak points are at 390.26, 640.45, 733.83, and 1250.47 °C, respectively. It decreased and then increased around first peak, where Ca(OH)\textsubscript{2} could lose water, and then, CaO reacted with oxidized organic sulfur to form CaSO\textsubscript{4}.\textsuperscript{22,23} The peak at 640.45 and 733.83 °C indicated that not only carbon combustion occurred at this time but also the reduction of iron oxide by CO might occur. The fourth peak might be the decomposition of CaSO\textsubscript{4} and the decomposition of CaSO\textsubscript{4} wrapped in iron−silicon complexes.

As indicated in Figure 3, the SO\textsubscript{2} evolved showed distinctive changes in trend at a temperature range of room temperature.
to 1300 °C. The stages of mass spectra of detected SO₃ evolved in were barely consistent with the stages of TG and DTG. A large amount of SO₂ was released during the raw coal combustion process, and the precipitation of SO₂ could be divided into two stages: 285.40–586.86 and 913.18–1300 °C. This was because of the reaction of FeS₂ and a part of organic sulfur with oxygen producing sulfates, oxides, and SO₂ at low temperatures (400 °C). Part of the stable organic sulfur and sulfate sulfur in the coal began to decompose at high temperatures, leading to a second SO₂ release peak. For coke, SO₂ precipitation was divided into three stages: 376.11–550.44, 550.44–713.70, and 112.98–1300 °C. Coke-Ca and coke-Ca-3%Al had no SO₂ release peak at 25–1157.98 °C, and this indicated that the addition of additives played a good role in sulfur fixation in a certain temperature range. Moreover, the release temperature region of coke-Ca-3%Al moved to the high temperature region, indicating that the addition of Al₂O₃ played a role in sulfur fixation at high temperatures.

The SO₂ emission is greatly reduced after the calcium–aluminum compound auxiliary agent is added to the coal. In order to obtain mineral compositions of coal and coke samples, the XRD of different ashes was conducted Figure 4. It shows that the XRD patterns of the raw coal ash mainly include Fe₂O₃ and Al₂Si₂O₇. The decomposition of CaCO₃ can be explained by the following facts: XRD patterns of coke contain CaO. This indicates that the CaCO₃ in coal is decomposed into CO₂ and CaO in the temperature range of 700–1000 °C. When CaCO₃ and Al₂O₃ compound additives are added to coal, the release of SO₂ decreases at high temperatures. The XRD phase of ash is Ca₂Al₂SiO₇. The results show that Ca₂Al₂SiO₇ has a certain sulfur fixation effect, which decreases SO₂ emission during coke-Ca-3%Fe combustion at high temperatures. We did a calorific test on the fuel, and the calorific value of clean coke is 23.67 MJ/kg, which meets the requirements of a civil fuel.

2.2. Influence Factor and Sulfur Forms of Coke. 2.2.1. Effects of Temperature on the Sulfur-Fixation Efficiency during Coke-Ca Combustion. The raw coal is added to calcium, and the clean coke is prepared by high-temperature pyrolysis. The effect of combustion temperature on sulfur retention of clean coke was investigated, as shown in Figure 5. It can be seen that as the combustion temperature increased from 600 to 1000 °C, the sulfur retention efficiency was kept almost constant at approximately 100%. However, when the combustion temperature exceeds 1000 °C, the sulfur fixation efficiency decreases significantly. This decreasing trend of sulfur fixation could be attributed to the enhanced CaSO₄ decomposition at higher temperatures. Therefore, it is urgent to improve the high-temperature sulfur fixation efficiency.

2.2.2. Effect of the Al₂O₃ Content on Sulfur Retention. Figure 6 shows the sulfur-fixation efficiency of the coke samples with different amounts of Al₂O₃ at 1050–1300 °C. The sulfur fixation efficiency decreases with the increase of Al₂O₃ content at 1100 °C but increases with the increase of the Al₂O₃ addition ratio from 1150 to 1300 °C. When the temperature is more than 1150 °C, adding excessive Al₂O₃ is unfavorable to sulfur fixation of clean coke combustion, but when the temperature is more than 1150 °C, excess Al₂O₃ is beneficial to sulfur fixation of clean coke. However, when the proportion of alumina exceeds 8%, it is unfavorable for sulfur fixation of clean coke. This indicates that alumina also has a "dual effect" on sulfur fixation in clean coke combustion, which is consistent with Liu’s study. On the whole, when the Ca/S is certain, it is advantageous to increase the sulfur fixation efficiency at high temperatures by increasing the proportion of Al₂O₃; the reason is that the Al will react with the CaSO₄ at high temperatures to form calcium sulfoaluminate. The calcium–aluminum composite additive can obviously improve the high-temperature sulfur fixation efficiency and reduce the SO₂ emission during the combustion process, so we wondered if aluminum alone could achieve the same effect. Next, we carried out systematic experiments on coke with different proportions of Al₂O₃.

2.2.3. Effect of the Al/S Molar Ratio on Sulfur Retention. Figure 7 shows the sulfur-fixation efficiency obtained from the desulphurization reaction by the feed of different Al/S molar ratios based on this experiment. Adding Al to raw coal has little effect on sulfur retention during the coal pyrolysis process, and the sulfur fixation efficiency of coke ash is lower than 3%,
which is lower than that of the clean coke itself. This further indicates that the addition of Al$_2$O$_3$ not only promotes the release of sulfur from coal during pyrolysis but also affects the release of sulfur from coke during combustion. Al$_2$O$_3$ is an acidic component of minerals and acid oxides in coal have little effect on sulfur release, which is consistent with the experimental results. Therefore, considering that calcium sulfoaluminate is difficult to decompose at high temperatures, CaCO$_3$ and Al$_2$O$_3$ are mixed with coal in a proper proportion.

2.2.4. Analysis of Sulfur Species for the Coke. The species of sulfur compounds in coal and coke were investigated using XPS. According to the binding energy signal, different sulfur compounds were identified using the following values of pyritic sulfur (162.5 ± 0.3 eV), thiophenic sulfur (164.1 ± 0.2 eV), sulfoxide sulfur (166.0 ± 0.5 eV), sulfone sulfur (168.0 ± 0.5 eV), and sulfate sulfur (169.5 ± 0.5 eV). Figure 8 shows a curve-fitting of XPS S 2p spectra of sulfur species on the surface of coke and coke-Ca-7%Al. As shown in Figure 8, the sulfur morphology in coke-Ca-7%Al is mainly composed of three categories: sulfides, thiophenes, and sulfones. Compared with coke, the peak height and area of sulfides increase, while those of thiophenes decrease and that of sulfone sulfur changes little. On the one hand, the compound additives increase the sulfide sulfur in the clean coke. On the other hand, the easily decomposed thiophene sulfur is released and converted into CaS. However, because of the presence of sulfone sulfur consuming the oxygen-containing functional groups during the coal pyrolysis process, no sulfate peak is seen in the figure, that is, CaS is not oxidized to CaSO$_4$.

The forms of minerals present in clean coke with different Al$_2$O$_3$ content are shown in Figure 9. It can be seen that the diffraction peaks of all samples mainly contain two kinds of minerals CaS and Ca(OH)$_2$ compared with the coke. XRD analysis suggests that the composite additives, especially CaCO$_3$, may react with sulfur in coal to generate CaSO$_4$, and Al can improve the release of organic sulfur during the pyrolysis of coal and form amorphous composite existing in coke. Meanwhile, the active CaO from the rest of the decomposed CaCO$_3$ can react with the water of pyrolysis to form calcium hydroxide. According to experimental investigation, the Ca(OH)$_2$ and CaS may be the main sulfur-fixation materials during the combustion of clean coke. In addition, the peaks of FeS in the XRD spectrum disappeared, which illustrated that the addition of Ca-based additives could catalyze the decomposition of partial Fe$_2$S or react directly with ferrous sulfide to form calcium sulfide, and the other part changes to calcium aluminate and Ca(OH)$_2$ in coke. It is considered that active CaO promotes the decomposition of FeS, which results in the formation of amorphous Fe–C by FeS. The solid–solid reaction also had some contribution to the result.

2.3. Effect of Combustion Temperature on Sulfur Fixation. Sulfur-fixation efficiency is plotted in Figure 10 as a function of temperature.
function of the temperature from 1050 to 1300 °C. The changing trends of the curves are roughly the same, that is, the sulfur fixation efficiency decreases with the increase of temperature. As shown in Figure 10, the sulfur-fixation falls sharply at 1200 °C. The reason for the lower efficiency of conventional sulfur-fixation product is the thermal decomposition of CaSO4 above 1200 °C. It is worth mentioning that, after adding 7% Al2O3 to the clean coke, the sulfur fixation efficiency slightly increases compared with the case in which 1−5% Al2O3 is added at 1150 °C. Meanwhile, at 1200 °C, the sulfur-fixation efficiency of adding Al2O3 in clean coke continued to drop off quick with the increasing temperature. The phenomenon can be interpreted to start generating resistance to the high-temperature phase calcium sulfoaluminate (3CaO-3Al2O3·CaSO4) as temperature increased from 1100 to 1325 °C on the basis of the conventional sulfur-fixation product (CaSO4). However, when the combustion temperature is above 1200 °C, the sulfur-fixation rate always descends rapidly first and then increases slowly from 1200 to 1300 °C. Because the thermal decomposition of CaSO4 is above 1200 °C, the high-temperature sulfur-fixation product at the temperature from 1200 to 1300 °C was mainly thought to be calcium sulfoaluminate (C4A3S). In addition, though the sulfur-fixation rate was relatively low (less than 50%) above 1200 °C, the sulfur-fixation rate of clean coke at the temperature range from 1050 to 1200 °C was very satisfactory, in which the efficiencies of all samples were more than 90% at the temperature of 1050 °C and more than 50% at 1200 °C. At the normal combustion temperature in the chain furnace, the sulfur removal rate of conventional burning coal by direct combustion is selected for XRD analysis. As can be seen in Figure 11, the main minerals are C4A3S, CaSO4, Ca2Al2SiO7 and so on. XRD analysis show that the diffraction peak of calcium sulfate (CaSO4) at the combustion temperature of 1200−1250 °C has been disappeared, and the peak of CaSO4 decreases gradually until it disappears from 1050 to 1250 °C. However, the main diffraction peak of C4A3S increased gradually from 1050 to 1250 °C. Also, the diffraction peak of calcium aluminosilicate (Ca2Al2SiO7) appears at the temperature above 1200 °C. XRD analysis suggests that at the combustion temperature below 1200 °C mainly contain CaSO4 and C4A3S, while the the sulfur-fixation products at combustion temperature above 1200 °C only contain C4A3S without CaSO4. That is to say, it is practicable to introduce calcium sulfoaluminate into the combustion process of clean coke that was prepared by adding Al2O3 and CaCO3 composite additives in advance to coal during the pyrolysis.

2.4. Mechanism of Sulfur Retention during Clean Coke Combustion. Figure 12 shows the chemical impact of Al2O3 on Ca-based sorbents.

![Figure 12. Schematic diagram demonstrating the chemical impact of Al2O3 on Ca-based sorbents.](https://dx.doi.org/10.1021/acsomega.9b04293)

Al2O3 on Ca-based sorbents for high-temperature sulfur fixation during clean coke combustion. On the one hand, CaS produced during pyrolysis and CaO decomposed by compound additives were oxidized during combustion, and CaO captured the SO2 released from clean coke combustion, which formed CaSO4. On the other hand, CaSO4 reacts with Al2O3 to produce calcium sulfoaluminate at high temperatures, which improves the sulfur fixation efficiency of clean coke combustion at high temperatures. At the same time, CaSO4 plays a leading role when temperature is under 1200 °C, while calcium sulfoaluminate plays a major role at above 1200 °C. CaSO4 produced by clean coke combustion reacts quickly with Al2O3 in a complex agent to produce the high-temperature stable phase of calcium sulfoaluminate, which is difficult to decompose once it is formed and the decomposition temperature is more than 1450 °C. Therefore, the melting or decomposition reaction does not occur at higher temperature, which greatly improves the sulfur fixation efficiency of clean coke at high temperature combustion.

3. CONCLUSIONS

In order to solve the problem of low sulfur fixation efficiency of clean coke at high temperatures, by adding different proportions of Al2O3 to coal samples, the effects of Al2O3 on sulfur fixation efficiency at different combustion temperatures are analyzed, and the coke ashes are examined through XRD. Simultaneously, the optimum experiment reveals that the Ca/S molar ratio 1.5 and the Al/S molar ratio below 1.5 (about 8%) as the best additive ratio. In this case, the sulfur fixation efficiency can reach 88% at 1050 °C and 72% at 1150 °C. The maximum sulfur fixation efficiency of clean coke is about 59% at 1200 °C and about 10% at 1300 °C, which is about 30% higher than that of traditional coal combustion at low temperature. At the same time, CaSO4 plays a leading role when temperature is under 1200 °C, while calcium sulfoaluminate plays a major role above 1200 °C. In a word, the addition of Al2O3 promotes the generation of C4A3S and prevents the pyrolysis of CaSO4 at high temperatures to a certain extent, greatly increasing the sulfur fixation efficiency.
4. EXPERIMENTAL SECTION

4.1. Raw Materials. A typical bituminous coal from Shanxi Province of China was used in this experiment. Prior to the pyrolysis experiments, the parent coals were subjected to the conventional proximate and ultimate analyses. The respective chemical properties of the coals are given in Table 1. The ash composition of coal is shown in Table 2. CaCO$_3$ (99 wt %, Kemiou Chemical Reagent Co. Ltd., China) and Al$_2$O$_3$ (Tianxing New Material Co. Ltd. Nanjing) were selected as the calcium additive.

| Table 1. Proximate and Ultimate Analysis of Coal Sample$^a$ |
|-----------------|-----------------|-----------------|-----------------|
| proximate analysis (wt %) | ultimate analysis (wt %) |
| $M$ | $A$ | $V$ | $FC$ | $C$ | $H$ | $O$ | $N$ | $S$ |
| 1.3 | 8.9 | 15.5 | 74.3 | 88.1 | 5.1 | 2.2 | 1.9 | 2.7 |

$^a$M, moisture; V, volatile; A, ash; FC, fixed carbon; ad, air-dried basis; and daf, dry-ash-free basis.

| Table 2. Analysis of Ash Composition in Coal (wt %) |
|-----------------|-----------------|-----------------|-----------------|
| SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | P$_2$O$_5$ | Na$_2$O | TiO$_2$ |
| 48.46 | 24.60 | 24.46 | 1.37 | 0.32 | 0.39 | 0.40 |

4.2. Methods. 4.2.1. Preparation of Clean Coke. First, the coal was ground to particles of size less than 3 mm. Then, 100 g of raw coal with a certain amount of CaCO$_3$ was mixed according to a given proportion of Ca/S molar ratio, and then, these mixtures were extruded into coal briquettes by an extruder. In this paper, the Ca/S molar ratio was equal to 1.5, the high-sulfur coal and CaCO$_3$ were taken and mixed according to a given proportion, and about 1, 3, 5, and 7% Al$_2$O$_3$ were added to coal samples. Then, the mixtures were extruded into coal briquettes by an extruder.

The pyrolysis experiments of coal samples were carried out in the furnace presented in Figure 13. Pyrolysis experiments were conducted in the furnace in ultra-high-purity N$_2$ (99.995%) obtained from coal samples at a heating rate of 10 $^\circ$C/min from room temperature to 800 $^\circ$C under N$_2$, and they lasted for 5 min. At this moment, these coal briquettes were placed in a high-temperature muffle furnace at a heating rate of 10 $^\circ$C/min from room temperature to different temperatures (1000, 1050, 1100, 1150, 1200, 1250, and 1300 $^\circ$C) and held for 1 h at each temperature to maximize the decomposition of volatiles. The ash residues were collected to measure the total sulfur content of ashes at different temperatures. This experiment used two methods to detect the total sulfur in coke: the rapid instrumental detection of sulfur and the Eshka method (Testing Standard of China GB/T214-2007). Because coke ash has a high-temperature-resistant sulfur fixation phase after combustion and the maximum temperature of total sulfur is 1150 $^\circ$C, the content of total sulfur in coke ash was determined by the Eshka method as follows. Ash (1.00 ± 0.01 g) was mixed with 3.00 g of Eshka agent (mNa$_2$CO$_3$/mMgO = 2:1). Then, this mixture was slowly heated so that sulfur in coke ash could be converted into soluble sulfate. Finally, the BaCl$_2$ solution was added at a certain acidity to transform the soluble sulfate into BaSO$_4$. The sulfur content in ash was calculated as eq 1

$$S_{(ash)} = \frac{(m_1 - m_2) \times 0.1374}{m} \times 100 \%$$

where $S_{(ash)}$ is the sulfur content in ash (%); $m_1$ is the weight of BaSO$_4$ (g); $m_2$ is the weight of BaSO$_4$ in blank test (g); $m$ is the weight of ash; and 0.1374 is the conversion factor of BaSO$_4$ to sulfur.

4.3. Analysis. The crystal structures of clean coke and coke ash were analyzed using an X-ray diffractometer (XRD, DX-2700x) with Cu K$_\alpha$ radiation (30 mA, 40 kV, $\theta$ = 0.15408 mm). The X-ray intensities were detected in a continuous scan over a range of 5.0$^\circ$ $\leq 2\theta \leq 85^\circ$ and a step size ($2\theta$) of 0.03$^\circ$.

XPS was used to determine and quantify organically formed sulfur functional forms present in raw coal and the respective transformation in clean coke brought by pyrolysis and combustion. In this experiment, XPS S 2p signals were acquired and recorded using an ESCALAB 250 X-ray photoelectron spectrometer of the United States Thermo VG Company. The XPS was performed with Al K$_\alpha$ radiation ($hv = 15$ kV) at 150 W; the spot is 500 $\mu$m.

The coal and coke samples were tested using a Setaram Evolution synchronous thermal analyzer manufactured by Setaram, France, at a heating rate of 10 $^\circ$C/min in air atmosphere. The room temperature range is from 20 to 1300 $^\circ$C. The TG–MS was used to analyze the temperature range of SO$_2$ released during the combustion of clean coke and to study
the release of sulfur gas during coal pyrolysis and clean coke combustion.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

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