TECHNICAL REPORT

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Project Title: Behavior of Sulfur and Chlorine in Coal during Combustion and Boiler Corrosion

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ABSTRACT

The purpose of this project is to conduct laboratory experiments to clarify the mechanism of boiler corrosion, which may lead to solving the corrosion problem associated with the utilization of Illinois' high-sulfur and high-chlorine coal. The kinetics of the release of sulfur and chlorine species during coal combustion is being determined in the laboratories using temperature-programmed pyrolysis coupled with quadrupole gas analysis (QGA) and thermogravimetric analysis in conjunction with Fourier transform infrared spectroscopy (FTIR). Samples of boiler deposits and ashes from different locations in boilers using Illinois coal will be analyzed for mineralogical and chemical compositions to understand the relations among deposit compositions, coal compositions, and the gaseous species in combustion gases. The relationship between the level of chlorine in Illinois coal and boiler corrosion will be studied by experiments with simulated combustion gases under combustion conditions. Reduction of sulfur and chloride concentrations in the flue gas using additives will also be evaluated.

During the first quarter, we conducted the pyrolysis-QGA experiments to determine the release profile of SO₂ from the high-chlorine coal IBC-109. The SO₂ was released from the coal between 250° and 650°C with a major peak at 510°C. Preliminary experiments on monitoring hydrogen chloride (mass 36) with a QGA were carried out; further experiments are planned to enhance the efficiency of HCl detection. The TG-FTIR experiments were completed on two coal samples: high-chlorine coal IBC-109 and low-chlorine coal IBC-106. The volatile species identified by FTIR spectroscopy include CO₂, CH₄, NH₃, SO₂, CO, H₂O, and HCl. The HCl in high chlorine coal was evolved between 400° and 650°C with a peak slightly below 490°C under the present pyrolysis conditions.

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EXECUTIVE SUMMARY

Many years of boiler experience have demonstrated that boiler corrosion is caused by the formation of alkali iron trisulfates and that a high-chlorine coal can enhance boiler corrosion. The mechanism of corrosion depends on the behavior of sulfur, chlorine, and alkali elements in the boiler environment. The nature of gaseous species of these elements and their kinetics of release depend primarily on temperature and oxidation conditions in the boiler.

The purpose of this project is to understand the mechanism of boiler corrosion caused by high-sulfur and high-chlorine coal. The initial tasks are to develop two methods for detecting the gaseous sulfur and chlorine species in combustion gases. The first method is temperature-programmed pyrolysis coupled with quadrupole gas analysis (QGA), which allows us to detect and monitor the release of sulfur and chlorine gases based on the masses of the gaseous species. The second method is thermogravimetry (TG) in conjunction with Fourier transform infrared spectroscopy (FTIR). Thermogravimetry provides a means for measuring heating condition and weight change. The combined TG-FTIR system has the capability of continuously monitoring the weight change of a coal sample as well as of quantitatively determining the gases evolved.

During the first quarter, the pyrolysis-QGA experiments were conducted to determine the release profile of SO_2 from the high-chlorine coal IBC-109. The SO_2 was released from the coal between 250° and 650°C with a major peak at 510°C . The identification of hydrogen chloride by monitoring the species of mass-36 on the quadrupole gas analyzer showed considerable complexity. Under a reducing condition a better peak of mass-36 was obtained. This peak is not caused by HCl , but by hydrogen sulfide of sulfur isotope ^{34}S (H_2^{34}S , total mass = 36). In order to monitor the HCl gas on the QGA without the interference from other gases, a specialty gas (N_2 with 950 ppm HCl) was used. It showed that the response of HCl was very slow because of the absorption of the HCl on the inside of the capillary. We plan to use capillary tubing with a larger diameter to enhance the detection of HCl .

The TG-FTIR experiments were carried out on two coal samples: the high-chlorine coal IBC-109 and the low-chlorine coal IBC-106. The volatile species identified include CO_2 , CH_4 , NH_3 , SO_2 , CO , H_2O , and HCl . The absorption peaks of HCl overlap with those of CH_4 . However, the intensity of the 2962 cm^{-1} peak is mainly due to HCl in IBC-109, because it is much stronger for this high-chlorine coal than that of the low-chlorine coal IBC-106. By comparing the gas evolution profiles of the 2962 cm^{-1} peak ($\text{HCl} + \text{CH}_4$) and the 1304 cm^{-1} peak (CH_4) of both high-chlorine and low-chlorine coals, the HCl evolution profile may be determined. It shows that HCl is evolved from the coal between 400° and 650°C with a peak slightly below 490°C under the pyrolysis conditions.

OBJECTIVES

The purpose of the project is to clarify the effect of chlorine and sulfur in Illinois coal on boiler corrosion and develop solutions to the problem. The specific goals of the project are to:

- Identify gaseous sulfur and chlorine species evolved from coal under various pyrolysis and combustion conditions.
- Determine the rate of release of sulfur and chlorine species during heating in oxidizing and reducing atmospheres.
- Determine the mineralogical and chemical compositions of slag and ash samples from boilers burning Illinois coal with various chlorine levels and forms of chlorine, and to relate the chlorine level in coal to boiler corrosion rate.
- Perform simulated corrosion tests to determine the effects of chloride concentration in combustion gas (which is dependent on the chlorine content in coal) on corrosion rate of steels.
- Evaluate pragmatic remedial measures to solve the chlorine-enhanced corrosion problem.

INTRODUCTION AND BACKGROUND

Approximately 95% of the coal resources in the Illinois Basin are high-sulfur coal, and a significant portion of the coal resources is also high in chlorine. At least half of the known economically minable coal reserves in Illinois have a high chlorine content ($>0.3\%$). Coal with such high chlorine content may be difficult to market because the chlorine may enhance boiler corrosion rate of metal tube walls in utility and industrial boilers. However, assessing the effect of chlorine in coal on boiler corrosion is a complex problem. There are many variables which may synergistically affect the corrosion rate in a boiler, and there is a lack of data to isolate individual factors.

Boiler corrosion is controlled by several other factors, in addition to the chlorine content, including temperature, oxidizing-reducing conditions, alkali contents, sulfur content, and ash composition. For several decades, chlorine-enhanced corrosion has been attributed to the presence of chloride which prevents the formation of a protective layer of oxides on metal surfaces. Direct HCl attack is also a potential corrosion mechanism. Chlorine-enhanced corrosion is believed

to be more significant under a reducing condition than under an oxidizing condition. Under the oxidizing condition, the metal surface is coated with a protective oxide layer, and corrosion is constrained by diffusion of corrosive gaseous species through the protective layer. In contrast, under the reducing condition the deposits on metal surfaces are a mixture of oxides and sulfides, which do not form as good a protective layer as compact oxides. Thus, corrosion can be significant in areas under a reducing atmosphere. The mechanism of boiler corrosion is related to the relative abundances of gaseous species (HCl, NaCl, KCl, Cl₂, SO₂, H₂S, etc.) in combustion gases, which in turn are related to the composition of feed coal and combustion conditions.

One important purpose of the proposed project is to perform laboratory experiments to determine the gaseous species in combustion gases and the kinetics of their release during combustion. Then, the relation between the chlorine and alkali levels in feed coal and boiler corrosion can be better understood. During the first quarter of this project our efforts were focused on the setting up laboratory equipment and developing experimental methods for determining volatile sulfur and chlorine compounds during pyrolysis.

EXPERIMENTAL PROCEDURES

Samples

Two coal samples from the Illinois Basin Coal Sample Program were used in the experiments: IBC-109 (1.13% sulfur, 0.42% chlorine) and IBC-106 (3.77% sulfur, 0.02% chlorine).

Kinetics of sulfur and chlorine release using temperature-programmed pyrolysis coupled with quadrupole gas analysis (QGA) (ISGS).

The pyrolysis-combustion apparatus used with the quadrupole gas analyzer (QGA) to study the gases released under pyrolysis and combustion conditions is capable of heating the coal sample from the ambient to about 850°C at different heating rates. Major components include a quartz tube reactor, a gas flow controller, two tube furnaces, a programmable temperature controller, 50-μm capillary tubing connecting the Dycor QGA to the pyrolysis system, and a microcomputer (Figure 1). A coal sample (approximately 0.5 grams) is heated nonisothermally under a controlled atmosphere (air, nitrogen, oxygen, or other gases) in the quartz-tube reactor which consists of two consecutive chambers. The coal is pyrolyzed in the first chamber under a nitrogen atmosphere and the volatile products are carried to the second chamber where they are combusted at 850°C under a constant flow of oxygen. The gaseous products are detected with a quadrupole gas analyzer. The data are transmitted to a microcomputer and

stored as ASCII files on the hard disk.

Identification of gaseous sulfur and chlorine species in combustion gas and determination of gas release profile using thermal gravimetry (TG) in conjunction with Fourier transform infrared spectroscopy (FTIR) (WKU).

Using the TG-FTIR system in the WKU laboratories, the gases produced on a DuPont-951 TGA are analyzed by FTIR spectroscopy using the Perkin Elmer-1600 FTIR spectrometer. Thermogravimetry provides a means for measurement of heating condition and weight change. The system is able to continuously monitor the weight change of a coal sample as well as to quantitatively determine the gases evolved (CO , CO_2 , SO_2 , H_2O , HCl , CH_4 , COS , C_2H_2 , C_2H_4 , and C_3H_6) during pyrolysis and combustion. The TGA furnace is connected to the 100 X 24 mm gas cell through a 1-mm Teflon tube. Both the Teflon line and the gas cell can be heated by heating coils up to 250°C . The time lag between the sample and the gas cell is one minute with a gas flow of 50 ml/min; the spectrum can be taken every minute. This also includes the time it takes to store the spectrum on the computer. Calibration of the FTIR is made using pure gases or prepared gas mixtures.

Approximately 100 mg of coal was used in each TG-FTIR experiment. The pyrolysis was conducted with a nitrogen gas (flow rate 25 mL/min), a temperature program from 20° - 900°C , a heating rate of $10^\circ\text{C}/\text{min}$. The FTIR scanning period was four seconds. Several filtering test tubes with gas dispersers were connected in a series with TG-FTIR to collect the combustion gases. The HCl vapor was trapped in 50 mL of 0.1% sodium carbonate solution and the chloride content was determined using an Ion Selective Analyzer and ion chromatography.

RESULTS AND DISCUSSION

Pyrolysis-Quadrupole Gas Analysis (QGA) experiments (ISGS)

During the first quarter of this project we completed several pyrolysis experiments using the quartz pyrolysis/combustion system shown in Figure 1. We concentrated on monitoring the release of sulfur compounds and hydrogen chloride from coal sample IBC-109 as the temperature was increased from the ambient to 850°C . The gaseous species were determined with the quadrupole gas analyzer (QGA). Because initial tests showed rather nonuniform heating rates, several trial runs were made without a coal sample to establish new input parameters for the temperature controller. Figure 2 compares three heating curves: the first curve (CL91002B) shows the stepping problem that initially occurred, the second curve (CL91018E) shows an improved heating profile with only one step during the heating period, and the third curve (TRIAL 29) shows a

smooth heating rate obtained after the new input parameters were established for the controller and furnace. If a steplike heating curve occurred during coal pyrolysis, volatiles in the coal would be released in a pulsating manner resulting in an erroneous multipeak gas-release profile. Once the correct input parameters were used, smooth heating curves were obtained which produced consistent release profiles of gases.

The pyrolysis-QGA experiments showed that at a heating rate of 50°C/min sulfur dioxide (SO₂) was released from coal IBC-109 primarily between 250° and 650°C (Figure 3). The SO₂ profile showed a small initial release of sulfur between 250° and 400°C followed by a larger peak between 400° and 550°C with a maximum at 510°C, and then by another smaller peak close to 625°C. The large central SO₂ peak is associated with the main release of volatiles from the coal. The smaller higher temperature peak is probably associated with the release of pyritic sulfur from the coal sample. The initial small broad peak of SO₂ is unusual but may be characteristic of this sample. Perhaps there is a significant amount of weakly bonded organic sulfur compounds which are released in the initial volatilization of IBC-109.

The initial results on using QGA to monitor the release of hydrogen chloride (HCl) gas were perplexing. Release profiles of HCl were obtained during the pyrolysis/combustion experiments; however, the detection of HCl was rather poor. The profiles were very close to background levels of detection for HCl gas (Figure 4). The experiments under a fully oxidizing condition indicated that the release of HCl was primarily between 300° and 600°C with a peak close to 500°C. Within this temperature range, the strong HCl peak coincided with the primary release of the volatiles from coal IBC-109 (Figure 3, the CO₂ profile).

In an attempt to improve the detection of HCl, we changed several different parameters on the pyrolysis/combustion system. In some cases, when the flow of oxygen (O₂) to combustion chamber was reduced or a partial vacuum was pulled on the entire system, the O₂ was consumed by the volatile gases to the point of depletion, which created a reducing condition. Under these reducing conditions, it appeared that a better profile of HCl (mass 36) was obtained. Figure 5 compares two profiles obtained for mass-36 (HCl): one under a total oxidizing condition and the other under a reducing condition. However, the improved mass-36 profile under the reducing condition may not be caused by HCl, but is probably due to the presence of other reduced gas species. Additional sulfur species, including COS (mass 60) and H₂S (mass 34) were also formed under the reducing condition. Figure 6 compares the profiles for SO₂ and COS under an oxidizing condition where the excess oxygen concentration in the combustion chamber never fell below 5 percent (Run 3) to a reducing condition (Run 4). An obvious peak was obtained for COS under the reducing condition of Run 4. The H₂S profile is more difficult to comprehend because of the presence of oxygen isotope ¹⁸O in the

oxygen flow. The combination of ^{18}O and ^{16}O gives a mass of 34 for oxygen ($^{16}\text{O}^{18}\text{O}$), the same as H_2S . Thus the profile of mass-34 will mimic that of O_2 (mass 32). When O_2 is consumed, the oxygen (mass 32) will drop to background levels as will the $^{16}\text{O}^{18}\text{O}$ profile (mass 34). Figure 7 shows this effect for masses 32 and 34 of a blank run where the oxygen flow was shut off between 400° and 625 °C. If H_2S is present under a reducing condition, a peak should occur in the mass-34 profile during the period of O_2 depletion. Figure 8 shows typical profiles of sulfur species, including mass 34, obtained when the O_2 was consumed during the experiment. The H_2S peak is observed in the trough of the mass-34 profile. As the rate of volatile gases released from the coal sample decreases, the O_2 concentration is no longer completely consumed and the reduced gas species disappear.

As stated above, under the reducing condition, a better profile was obtained for the species of mass 36. However, this improved profile of mass-36 is probably not due to HCl . With the occurrence of H_2S under the reducing condition, the enlarged peak of mass-36 (Figure 8) is most probably a result of the presence of the naturally occurring heavy sulfur isotope ^{34}S in the hydrogen sulfide (H_2^{34}S , total mass = 36).

In order to use QGA for HCl detection without interference from other gases, a cylinder of 950 ppm hydrogen chlorine in nitrogen was obtained. Initially, the QGA did not detect any HCl from the new cylinder. However, after several minutes of continuous flow of the $\text{N}_2\text{-HCl}$ gas, a gradual increase was observed for the signal of mass-36, and, after two hours, a good HCl peak had developed on the monitoring screen of the QGA. However, after the two hour saturation period, we switched the $\text{N}_2\text{-HCl}$ flow on and off and still obtained a relatively slow response time for HCl detection. Additional changes were made to the system to reduce the travel pathway to the QGA and reduce the amount of metal with which the gas would come into contact. Still, the HCl response did not improve. The problem appears to be associated with the capillary tubing and is probably due to adsorption and desorption on the inside of the capillary.

We are currently pursuing alternative approaches for detecting HCl . Using capillary tubing with a larger inner diameter may improve the response time for detecting HCl . This will be tested during the early part of the second quarter. A second alternative which we are also considering is to use an ion-selective electrode for chloride detection. The exit gas from the pyrolysis-combustion system will still be sampled by the capillary for QGA analysis, and then flow directly through a flask containing a sodium carbonate solution to trap the chloride ions. The concentration of chloride ions collected in the solution will be measured using an ion-selective electrode connected to an ion meter with a serial port. The serial port will allow data acquisition from the ion-selective electrode by the same computer that is used to control QGA and temperature data. This

second approach will be pursued if the larger capillary tubing does not significantly improve the response time for HCl detection.

TGA-FTIR experiments (WKU)

The thermogravimetric curves of samples IBC-109 and IBC-106 are shown in Figure 9. The temperature of the maximum rate of weight loss ($T_{\max}$), % weight loss, and the maximum rate of the weight loss ($R_{\max}$) in %/min are listed in Table 1. Two samples have similar curves of weight loss, but their amounts of weight loss and rates of weight loss are slightly different. Weight loss occurs in two major temperature ranges: between 20° and 150°C and between 350° and 850°C. In the 20°-150°C range, sample IBC-109 had a weight loss of 4.23%, and IBC-106 6.4% as a result of the loss of moisture. The second weight loss occurred in the temperature range of 350° - 850°C, sample IBC-109 had a weight loss of 26.1% and IBC-106 32.3%. These weight losses correspond to the loss of the volatile matter, and are comparable to the volatile matter content of the coals determined with the Leco MAC-400 analyzer (32.0% of IBC-109 and of 35.9% of IBC-106 on an as-received basis).

Table 1. Results of TG/DTG analysis on coal samples IBC-109 and IBC-106.

Sample	Temp. Range	$T_{\max}$	Weight Loss (%)	$R_{\max}$
IBC-109	20.0°-149.8°C	87.1°C	4.2	0.56%/min
	149.8°-351.0°C		1.7	
	351.0°-889.7°C	450.5°C	26.1	1.26%/min
IBC-106	20.0°-150.0°C	87.1°C	6.4	0.85%/min
	150.0°-348.7°C		1.5	
	348.7°-833.1°C	422.4°C	32.3	2.71%/min

The gases evolved from coal during pyrolysis were identified by FTIR spectroscopy. Figure 10 shows the FTIR spectra of two samples at about 490°C. The volatile species identified include carbon dioxide (CO_2 , with the strongest peak at 2360 cm^{-1}), carbon monoxide (CO , 2177 cm^{-1}), sulfur dioxide (SO_2 , 1346 cm^{-1}), methane (CH_4 , 1304 cm^{-1}), ammonia (NH_3 , 952 cm^{-1}), water moisture (H_2O , 1441 cm^{-1}), and hydrogen chloride (HCl , 2962 cm^{-1}).

The gas release profiles from coal IBC-109 determined by TG-FTIR analysis is shown in Figure 11, and those for sample IBC-106 are shown in Figure 12. A quantitative identification of HCl however, is not straightforward because both CH_4 and HCl have an absorption peak at 2962 cm^{-1} . In order to resolve the contribution of each gas to the peak, the FTIR spectra of pure CH_4 and HCl were determined (Figure 13). Absorption peaks of methane occur in two regions: region 1 with wavenumbers from 3207 to 2679 cm^{-1} , and region 2 from 1392 to 1180 cm^{-1} . Absorption peaks of hydrogen chloride have wavenumbers from 3085 cm^{-1} to 2679 cm^{-1} . So the absorption peaks of HCl overlap with the peaks in the region 1 of CH_4 .

In determining CH_4 gas, some peaks in the region 2 (such as 1304 or 1269 cm^{-1}) can be used; the CH_4 release profiles (peak intensity versus temperature) for IBC-109 and IBC-106 are shown in Figures 11 and 12, respectively. The gas release profile of HCl may be established as described in the following. First, the behavior of the peaks in the region 1 where peaks of CH_4 and HCl overlap may be compared with the peaks in the region II (CH_4). The gas release profiles of IBC-109 are shown for the 1304 cm^{-1} and 1269 cm^{-1} peaks from the region 2 (CH_4), and the 2962 cm^{-1} peak from region 1 ($\text{CH}_4 + \text{HCl}$) (Figure 14). Both profiles of 1304 cm^{-1} and 1269 cm^{-1} (CH_4) have a peak at 550°C with different intensities. In contrast the profile of 2962 cm^{-1} ($\text{HCl} + \text{CH}_4$) has a peak at 490°C . This temperature is significantly lower than the 550° peaks of CH_4 . Thus, the 490°C peak of 2962 cm^{-1} is mainly due to HCl, with a limited component of CH_4 . Furthermore, the intensity ratio between the 2962 cm^{-1} and 1304 cm^{-1} peaks of the high-chlorine coal IBC-109 is 0.67; this is much larger than a ratio of 0.30 for the low-chlorine coal IBC-106 (Figure 15). Hence, the higher intensity of the 2962 cm^{-1} peak of IBC-109 is caused by its higher chlorine content (0.42%) than that of IBC-106 (0.02%). The HCl release profile may be obtained by subtracting the CH_4 component from the profile of 2962 cm^{-1} . This will be pursued during the next quarter. The resulting profile should be close to that of curve II in Figure 15. The HCl gas appears to be released between 400° and 650°C with a peak slightly below 490° during pyrolysis.

CONCLUSIONS AND RECOMMENDATIONS

The pyrolysis-QGA experiments were conducted to determine the release profile of SO_2 from high-chlorine coal IBC-109. The SO_2 is released from coal between 250° and 650°C with a major peak at 510°C . The detection of hydrogen chloride using the species with mass-36 on the quadrupole gas analyzer showed considerable complexity. Under a reducing condition, a better peak of mass-36 was obtained. However, this peak is not caused by HCl, but by hydrogen sulfide with sulfur isotope ^{34}S (H_2^{34}S , total mass=36). In order to monitor the HCl gas on the QGA, a specialty gas (N_2 with 950 ppm HCl) was used. It showed that the

response of HCl was very slow probably because of the adsorption of the HCl on the inside of the capillary tube. We plan to use capillary tubing with a larger diameter to enhance the detection of HCl.

The thermogravimetry-Fourier transform infrared (TG-FTIR) experiments were carried out on two coal samples: the high-chlorine coal IBC-109 and the low-chlorine coal IBC-106. The volatile species identified by the FTIR spectroscopy include CO_2 , CH_4 , NH_3 , SO_2 , CO , H_2O , and HCl. The absorption peaks of HCl overlap with those of CH_4 . However, the 2962 cm^{-1} peak is mainly due to HCl because this peak is stronger for the high-chlorine coal IBC-109 than that of the low-chlorine coal IBC-106. The gas release profile of 2962 cm^{-1} has a peak at 490° , significantly lower than that of wavenumber 1304 cm^{-1} (CH_4). We will obtain the HCl release profile by subtracting the CH_4 component from the 2962 cm^{-1} profile following appropriate calibration. The resulting peak should be close to curve II of Figure 15. It appears that HCl in high chlorine coal was evolved between 400° and 650°C with a peak slightly below 490°C during pyrolysis. In the next quarter, we will also work on the mass balance of HCl release from coal during pyrolysis.

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Figure 1. The experimental setup for temperature-programmed pyrolysis coupled with quadrupole gas analysis (QGA). Major components include a quartz tube reactor, a gas flow controller, two tube furnaces, a programmable temperature controller, a capillary tube connecting the Dycor QGA to the pyrolysis system, and a microcomputer. The reactor consists of two consecutive chambers. A coal sample is heated nonisothermally under a controlled atmosphere in pyrolysis chamber under a nitrogen or another inert gas atmosphere and the volatile products are carried to the combustion chamber where they are combusted at $850^\circ C$ under a constant flow of oxygen. The gaseous products, including CO_2 , SO_2 , HCl , and other gaseous compounds, are detected with a quadrupole gas analyzer. The data are processed on a microcomputer.

Figure 2. Temperature profiles showing the progressive improvement of heating rates with changes of input parameters to the controller.

Figure 3. Profiles of CO₂ and SO₂ (X100) under the oxidizing condition at a heating rate of 50°C/min.

Figure 4. Two typical HCl profiles obtained under a highly oxidizing condition.

Figure 5. HCl profiles under highly oxidizing (003C) and partially reducing (004D) conditions. The maximum and minimum oxygen concentrations obtained are shown in the parentheses.

Figure 6. SO₂ and COS profiles during oxidizing (Run 3) and reducing (Run 4) conditions.

Figure 7. Profiles of masses 32 and 34(*100) during a blank run where O₂ flow was shut off between 400° and 625°C.

Figure 8. Gas profiles obtained under a reducing a condition. Mass numbers in parentheses are used for profiles that possibly represent more than one gaseous species.

Figure 9. The thermogravimetric curves of coals IBC-109 and IBC-107.

Figure 10. The TG-FTIR spectra of coals IBC-109 and IBC-106.

Figure 11. Gas release profile by TG-FTIR analysis for the high-chlorine coal IBC-109.

Figure 12. Gas release profiles by TG-FTIR analysis for the low-chlorine coal IBC-106.

Figure 13. The FTIR spectra of CH_4 and HCl .

Figure 14. Release profile of CH_4 (1304 cm^{-1} and 1269 cm^{-1}) and the $\text{HCl} + \text{CH}_4$ (2962 cm^{-1}) by TG-FTIR analysis of coal IBC-109.

Figure 15. Comparison of gas release profiles of IBC-109 and IBC-106. Curve II is the profile mainly due to HCl (2962 cm^{-1}) from coal IBC-109.

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