Oxidation of Zhundong subbituminous coal in aqueous Fe^{2+} / glacial acetic acid solution with H_2O_2

Shuai Chen

Harbin Institute of Technology

Wei Zhou

Harbin Institute of Technology

Guang-Bo Zhao

Harbin Institute of Technology

Jihui Gao (✉ gaojh@hit.edu.cn)

Harbin Institute of Technology <https://orcid.org/0000-0002-0092-9472>

Research

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Abstract

The improvement of the reactivity of H_2O_2 and Zhundong subbituminous coal (ZS) was focused on in this work. The mild oxidation of ZS was carried out under different conditions. The liquid oxidation products were analyzed using gas chromatography /mass spectrometry (GC/MS). The results suggest that Fe^{2+} and glacial acetic acid (GAA) have a synergistic effect on the H_2O_2 oxidation of ZS, which can significantly promote the conversion of ZS and the production of liquid products. In total, 40 compounds are identified, which could be categorized as 8 group components. Most of them are valued-added chemicals. Among the detected compounds, carboxylic acids (CAs) is the most abundant, accounting for 47.22% of all the group components in TRC. Moreover, according to the compounds detected by GC/MS, condensed aromatic rings are significantly abundant than aliphatic moieties in organic matter of ZS. $-\text{CH}_2\text{CH}_2-$ are predominant bridged linkages connecting aromatic rings in ZS. The existing forms of organic nitrogen and sulfur species contain quinolins, pyrroles, pyrimidins, quinoxalines, enamides, oxazoles, isoquinolines, thiazols, sulfonamides in ZS.

1. Introduction

Low-rank coals (LRCs) are plentiful fossil resources, but they have low calorific value, high water content, high ash yield, poor thermal stability, and easy spontaneous combustion, which make LRCs difficult in the current industrial use, such as combustion, pyrolysis and gasification (Doskočil et al. 2014; Liu et al. 2019b; Liu et al. 2016; Liu et al. 2013a; Liu et al. 2013b; Liu et al. 2013c; Liu et al. 2018; Liu et al. 2015; Mae et al. 2001; Miura et al. 1996; Wang et al. 2013; Wang et al. 2012; Wang et al. 2014; Yu et al. 2014). Therefore, it is necessary to exploit a new conversion method for utilizing LRCs efficiently based on its structural characteristics (Liu et al. 2019b; Liu et al. 2018).

As is known to all, oxygen-containing functional groups, such as $-\text{OH}$, $-\text{COOH}$, $-\text{COOR}$, etc., are abundant in LRCs, which make LRCs have the potential to produce value-added oxygenated organic chemicals via the liquid oxidation (Doskočil et al. 2014; Liu et al. 2016; Mae et al. 2001; Miura et al. 1996). Hence, the oxidation of LRCs have attracted much attention from researchers. Classified by the kinds of oxidants, the method of oxidative depolymerization of LRCs includes $\text{RuCl}_3\text{-NaIO}_4$ oxidation (Huang et al. 2008; Liu et al. 2014; Lv et al. 2016; Murata et al. 2001; Stock and Wang 1986), O_2 oxidation (Wang et al. 2013; Wang et al. 2012), NaClO oxidation (Liu et al. 2013a; Lv et al. 2018; Wang et al. 2014; Yao et al. 2010) and H_2O_2 oxidation (Doskočil et al. 2014; Liu et al. 2019b; Liu et al. 2018; Liu et al. 2015; Mae et al. 2001; Miura et al. 1996; Tahmasebi et al. 2015; Wang et al. 2018). The high cost of $\text{RuCl}_3\text{-NaIO}_4$ makes it difficult for industrial applications. O_2 oxidation of LRCs needs high temperature, high pressure and strong acids or alkalis. NaClO oxidation of LRCs produces large amount of chloro-substituted species, leading to the difficulties in separating liquid oxidation products (Liu et al. 2015; Wang et al. 2015b). H_2O_2 oxidation of coal can be carried out at mild condition, and cannot be involved in other elements except H and O. Moreover, H_2O_2 is low price, easy availability, and eco-friendliness. Based on the above factors, H_2O_2 oxidation is a suitable way to utilize LRCs.

Miura et al. (Miura et al. 1996) found that the oxidation of LRCs using H₂O₂ under mild conditions could produce small molecule fatty acids in high yield and in high selectivity in 1996. After that, H₂O₂ oxidation of coal was used to produce carboxylic acids, including aliphatic carboxylic acids and benzenepolycarboxylic acids, and reveal molecular structure of coal (Doskočil et al. 2014; Liu et al. 2018; Liu et al. 2015; Wang et al. 2015b; Wang et al. 2018). However, to our knowledge, few reports were issued on improving the reactivity of H₂O₂ and coal.

Oxidation of coal with H₂O₂ was a free radical reaction, which hydroxyl radicals ($\cdot\text{OH}$), derived from the decomposition of H₂O₂, reacted with coal to achieve oxidative depolymerization of coal (Liu et al. 2018; Pan et al. 2013). Fe²⁺ is prone to catalyze H₂O₂ decomposition to form $\cdot\text{OH}$, as shown in Eq. 1 (Jiang et al. 2013). Moreover, the yield of the liquid products abundant in value-added organic chemicals produced via oxidative depolymerization of coal with H₂O₂ is improved with the aid of glacial acetic acid (GAA) (Liu et al. 2015). In this paper, we extend the above ideas and propose to improve the yield of liquid products produced through H₂O₂ oxidation of coal by introducing Fe²⁺ and GAA. We investigated conversion of Zhundong subbituminous coal (ZS) at different reaction conditions and the liquid products were separated and analyzed with gas chromatography/mass spectroscopy (GC/MS). The result suggests that Fe²⁺ and GAA exists in a synergistic effect on the oxidation of ZS in aqueous H₂O₂ solution, which can significantly promote the conversion of ZS and the production of liquid products.

2. Materials And Methods

2.1 Materials

ZS was collected from Zhundong Coal Mine in Xinjiang Province, China. It was pulverized to pass through a 200-mesh sieve (<74 μm) and then dried in a vacuum oven at 80 °C for 24 h before use. The proximate and ultimate analyses of the samples are listed in Table 1. H₂O₂ (30%), FeSO₄·7H₂O, glacial acetic acid (GAA), butanone, anhydrous MgSO₄, Na₂SO₃, diethyl ether and diazomethane are analytical reagents. All the reagents were purchased from Aladdin. All the organic solvents were distilled before use.

Table 1 Proximate and ultimate analyses (wt%) of ZS

sample	Proximate analysis				Ultimate analyses (d)				
	M_{ad}	A_{ad}	V_{ad}	FC_{ad}	C	H	N	S	O ^a
ZS	15.87	3.71	27.36	53.06	72.50	3.56	0.69	0.49	22.76

d: dry base; ad: air dried base.

^a By difference.

2.2 Experimental procedure

As displayed in Fig. 1, ZS (1 g), $FeSO_4 \cdot 7H_2O$ (0.06 g) and GAA (10 mL) were added to a 100 mL three-necked spherical flask under magnetic stirring. While stirring the mixture, 30% H_2O_2 (20 mL) was dropwise added into the mixture using a constant pressure drop funnel. The oxidation was performed in a water bath at 60 °C. After the reaction for 4 h, 2g Na_2SO_3 was added into the reaction mixture to resolve excess H_2O_2 , then the reaction mixture was separated by filtration to afford filter cake (FC) and filtrate (F). The FC was dried in a vacuum oven at 80 °C for 24 h. F was extracted five times with 100 mL butanone to attain extraction solution (ES). ES were dried with anhydrous $MgSO_4$ and filtrated to remove $MgSO_4 \cdot nH_2O$. Then the organic solvents in ES were removed by rotary evaporation to attain liquid products (E). Finally, E was methylated with diazomethane in diethyl ether to afford methyl esterified E (MEE) (Wang et al. 2015a).

The conversion of coal, and the yield and selectivity of E were calculated using the following Equations.

$$\text{Conversion} = (m_0 - m_1) / m_0 \times 100\% \quad (2)$$

$$\text{Yield} = m_2 / m_0 / (1 - M_{ad} - A_{ad}) \times 100\% \quad (3)$$

$$\text{Selectivity} = \text{Yield} / \text{Conversion} \times 100\% \quad (4)$$

where m_0 , m_1 and m_2 are the weights of raw coal, FC and E, respectively.

2.3 Sample analyses

MEE was analyzed using an Agilent 7890/5977 GC/MS equipped with a DB-EUPAH capillary column and a quadrupole mass analyzer with a split flow rate of 10:1, a flow velocity of 1.0 mL/s, and operation under electron bombardment (70 eV) mode. The mass scanning range was from 30 to 500 amu. and the electron bombardment voltage is 70 eV. The capillary column was held at 45 °C for 3 min, and then heated at 10 °C min⁻¹ from 45 to 310°C, and held at 310 °C for 20 min. Data were obtained and processed using GC/MS software, and the compounds were identified by comparing the mass spectra to the NIST05 spectral library data and referring to available references. The relative content (RC) of the compound was determined by normalization of the peak area, which was defined as the peak area of the compound divided by the sum of the peak areas of all identified compounds in the total ion chromatogram (Wang et al. 2015b). The total relative content (TRC) was acquired by the sum of the RC from a class of compounds.

3. Results And Discussion

3.1 Oxidation of Zhundong subbituminous coal

Conversion of ZS at different reaction conditions is shown in Table 2. When ZS is converted into liquid products abundant in value-added organic chemicals with H₂O₂ as oxidant, conversion of ZS is dependent on the amount of the amount of hydroxyl radicals ($\cdot$ OH) derived from the decomposition of H₂O₂. The more the amount of $\cdot$ OH produced the decomposition of H₂O₂, the higher the conversion of ZS. In the absence of FeSO₄·7H₂O and GAA (entry1, Table2), the conversion is 31.84% and the yield of liquid products is 15.06%, which could be related to the rate at which H₂O₂ decomposes to $\cdot$ OH is slow at current reaction conditions. $\cdot$ OH can be rapidly generated from the decomposition of H₂O₂ with the aid of Fe²⁺. Therefore, the addition to FeSO₄·7H₂O into the mixture of ZS and H₂O₂ aqueous solution (entry2, Table2) increases the ZS conversion to 72.31%. Miura et al. (Miura et al. 1996) proposed that H₂O₂ first broke weak -C-O- linkage to produce a large

amount of water-soluble organic compounds and CO₂, and a plurality of carboxylic groups are formed around the condensed aromatic rings of the compound. Then, the aromatics rings with the carboxylic groups gradually decomposed to produce small molecule fatty acids. At the same time, when the amount of ·OH produced from the decomposition of H₂O₂ is excessive, water-soluble organic compounds and small molecule fatty acids are further oxidized into CO₂. Under present experimental conditions, the excessive H₂O₂ is used, thus large amounts of ·OH are generated in the presence of Fe²⁺, which not only enhances the conversion of ZS, but also leads to the deep oxidation of liquid products. Therefore, though the conversion of ZS is very high, the yield and selectivity of liquid products is 9.74% and 13.46%, respectively (entry2, Table2). Interestingly, when adding FeSO₄·7H₂O and GAA into the mixture of ZS and H₂O₂ aqueous solution, the conversion of ZS is 75.18%, and the yield and selectivity of liquid products is 59.49% and 79.13%, respectively (entry3, Table2). The result indicates that there is a synergistic effect of Fe²⁺ and GAA, which can significantly promote the conversion of ZS and the production of liquid products.

Table 2 Conversion of ZS at different reaction conditions

entry	30% H ₂ O ₂	FeSO ₄ ·7H ₂ O	GAA	Conversion	Yield	Selectivity
	/mL	/ g	/ mL	/%	/%	/%
1	20	0	0	31.84	15.06	47.31
2	20	0.06	0	72.31	9.74	13.46
3	20	0.06	10	75.18	59.49	79.13

3.2 GC/MS analysis

As displayed in Fig. 2 and Table 3, 40 compounds are identified by GC/MS analysis in total. Their parent products can be classified into hydrocarbons (HCs), alkanoic acids or

alkenoic acids (AAs), alkanedioic acids or alkenedioic acids (ADAs), alkanetricarboxylic acids or alkenetricarboxylic acids (ATCAs), benzene carboxylic acids (BCAs), nitrogen containing species (NCSs), sulfur containing species (SCSs), and others species (OSs) (Liu et al. 2019a; Liu et al. 2013b; Liu et al. 2013c; Wang et al. 2014).

As shown in Table 3 and Fig. 3, 19 carboxylic acids (CAs) are detected by GC/MS analysis, including 2 AAs, 7 ADAs, 3 ATCAs and 7 BCAs. CAs is the most abundant, accounting for 47.22% of all the group components in TRC. Arylalkenes or arylalkanes, α,ω -diarylalkenes or α,ω -diarylalkanes and condensed aromatics are the precursors of AAs, ADAs and BCAs, respectively (Liu et al. 2013b). Pan et al. (Pan et al. 2013) proposed the mechanism of the H_2O_2 oxidation: First, $\cdot OH$ are produced from the decomposition of H_2O_2 . Then, $\cdot OH$ reacts with the cluster ring, producing a large amount of water-soluble organic compounds. Meanwhile, Liu et al. (Liu et al. 2018) supposed that $\cdot OH$ can break condensed aromatic rings in Xianfeng lignite-derived residue followed by rupturing the condensed aromatic rings to produce aromatic carboxylic acids. Among the detected CAs, BCAs are the most abundant in detected compounds, accounting for 34.89% of all group components in TRC, suggesting that that condensed aromatic rings are significantly abundant than aliphatic moieties in organic matter of ZS. Interestingly, benzene-1,2,3,4,5,6-hexacarboxylic acid, accounts for 25.03% of all the group components in TRC. The resulting benzene-1,2,3,4,5,6-hexacarboxylic acid could be derived from the oxidation of highly condensed aromatic rings (Scheme 1). Among the detected ADAs, succinic acid is predominate, accounting for 4.3% of all the group components in TRC, implying that $-CH_2CH_2-$ is dominant bridged linkages connecting aromatic rings in ZS. Moreover, most of the detected CAs are valued-added chemicals. For example, palmitic acid can be used as a precipitant, chemical reagent and waterproofing agent. Succinic acid can be used to produce surfactant, detergent additive and foaming agent. Benzene-1,2,3,4,5,6-hexacarboxylic acid is a useful polydentate ligand (Liu et al. 2018).

As shown in Table 3 and Fig. 3, 7 HCs, 8 NCSs and 6 SCSs were detected by GC/MS analysis, respectively. According to the detected NCSs and SCSs, we deduce that the

existing forms of organic nitrogen and sulfur species in ZS contain quinolins, pyrroles, pyrimidins, quinoxalines, enamides, oxazoles, isoquinolines, thiazols, sulfonamides. Moreover, some of them are useful chemicals. For example, (Z)-docos-13-enamide, which accounts for 10.21% of all the group components in TRC, can be used as an excellent lubricant for extruded films of polyvinyl chloride, polyethylene and polypropylene.

[Please see the supplementary files section to view Scheme 1.]

Table 3 Compounds detected in the product from ZS oxidation with H_2O_2 in the presence of Fe^{2+} and GAA. Reaction conditions: ZS, 1g; temperature, 60 °C; 30% H_2O_2 , 20 mL; $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 0.06g; oxidation time, 4 h; glacial acetic acid, 10 mL.

Peak	Parent compound	Relative content/%
HC		
19	icosane	0.22
22	henicosane	0.49
27	docosane	0.87
31	tricosane	1.08
32	tetracosane	1.14
33	pentacosane	0.84
37	hexacosane	0.69
AA		
18	3-(2-hydroxyethoxy)-3-oxopropanoic acid	0.7
20	palmitic acid	0.36
ADA		
1	fumaric acid	0.38
2&8&11	2-hydroxysuccinic acid	1.36
3&4	2,3-dihydroxysuccinic acid	0.81
6	maleic acid	0.29
7&21&26	succinic acid	4.3
10	4-oxoheptanedioic acid	0.25
14&15	5-oxotetrahydrofuran-2,3-dicarboxylic acid	0.8
ATCA		
9&25	2-hydroxypropane-1,2,3-tricarboxylic acid	0.75
12&13	1-hydroxypropane-1,2,3-tricarboxylic acid	0.73
24	propane-1,2,3-tricarboxylic acid	1.6
BCA		
5	phthalic acid	0.29
28&29	benzene-1,2,4-tricarboxylic acid	3.55
30	benzene-1,3,5-tricarboxylic acid	1.14

35&36	benzene-1,2,3,5-tetracarboxylic acid	1.5
38	benzene-1,2,3,4-tetracarboxylic acid	0.94
39	2,2'-(isophthaloylbis(oxy))diacetic acid	2.44
49&51&54&56	benzene-1,2,3,4,5,6-hexacarboxylic acid	25.03
NCSs		
16	2-methylquinolin-3-ol	0.43
17	quinoline-2-carboxylic acid	0.29
40&42&43	ethyl 9-methyl-1-phenyl-1,2,3,3a,9,9a-hexahydro-4H-pyrrolo[2,3-b]quinoxaline-4-carboxylate	6.48
44	5-benzyl-4,6-diphenylpyrimidin-2(1H)-one	11.82
48	2,3,8,9-tetramethoxy-11,12-dihydrobenzo[c]phenanthridin-6(5H)-one	1.04
50	(Z)-docos-13-enamide	10.21
52	7-(4,5-dimethoxy-2-methylnaphthalen-1-yl)-3-methyl-1,2,3,4-tetrahydroisoquinolin-8-ol	0.82
53	7-methyl-6,7,7a,8-tetrahydro[1,3]dioxolo[4,5-i][1,3]dioxolo[4',5':5,6]indeno[2,1-c][2]benzazepine	4.13
SCSs		
23	N,4-dimethylbenzenesulfonamide	5.41
45	(Z)-6,7-dimethyl-2-(3-nitrobenzylidene)benzo[4,5]imidazo[2,1-b]thiazol-3(2H)-one	2.08
47	2,4-dimethylbenzo[4,5]imidazo[1,2-c]pyrido[3',2':4,5]thieno[2,3-e]pyrimidine	0.8
55	N,4-dimethyl-N-tosylbenzenesulfonamide	0.89

OSs		
34	dimesitylmethanone	0.89
41&46	bis(6-methylheptyl) phthalate	2.16

4. Conclusion

Fe^{2+} and GAA have a synergistic effect on the H_2O_2 oxidation of ZAS, which can significantly promote the conversion of ZS and the production of liquid products. More organic matter is converted into soluble species, including HCs, AAs, ADAs, ATCAs, BCAs, NCSs, SCSs and OSs) by oxidation of ZS with H_2O_2 in the presence of Fe^{2+} and GAA. In total, 19 carboxylic acids (CAs) are detected by GC/MS analysis, including 2 AAs, 7 ADAs, 3 ATCAs and 7 BCAs. Among the detected compounds, CAs is the most abundant, accounting for 47.22% of all the group components in TRC. Moreover, according to the compounds detected by GC/MS, condensed aromatic rings are significantly abundant than aliphatic moieties in organic matter of ZS. $-\text{CH}_2\text{CH}_2-$ is predominant bridged linkages connecting aromatic rings in ZS. The existing forms of organic nitrogen and sulfur species contain quinolins, pyrroles, pyrimidins, quinoxalines, enamides, oxazoles, isoquinolines, thiazols, sulfonamides in ZS.

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References

- Doskočil L, Grasset L, Válková D, Pekař M (2014) Hydrogen peroxide oxidation of humic acids and lignite Fuel 134:406-413.
- Huang YG et al. (2008) Ruthenium ion-catalyzed oxidation of shenfu coal and its residues Energy & Fuels 22:1799-1806.
- Jiang CC, Gao Z, Qu HL, Li JW, Wang XX, Li P, Liu H (2013) A new insight into Fenton and Fenton-like processes for water treatment: Part II. Influence of organic compounds on Fe(III)/Fe(II) interconversion and the course of reactions Journal of Hazardous Materials 250-251:76-81.

Liu F-J et al. (2014) Characterization of organonitrogen species in Xianfeng lignite by sequential extraction and ruthenium ion-catalyzed oxidation Fuel Processing Technology 126:199-206.

Liu FJ, Zong ZM, Li WT, Zhu XN, Wei XY, Tang MC, Huang ZX (2019a) A three-step dissociation method for converting Xiaolongtan lignite into soluble organic compounds: Insights into chemicals, geochemical clues, and structural characteristics Fuel 242:883-892.

Liu F et al. (2019b) Characterization of organic compounds from hydrogen peroxide-treated subbituminous coal and their composition changes during microbial methanogenesis Fuel 237:1209-1216.

Liu FJ, Wei XY, Fan MH, Zong ZM (2016) Separation and structural characterization of the value-added chemicals from mild degradation of lignites: A review Applied Energy 170:415-436.

Liu FJ et al. (2013a) The Effect of Pretreatment with H_2O_2 on the Oxidation of Shenfu Subbituminous Coal with NaOCl Energy Sources Part a-Recovery Utilization And Environmental Effects 35:1967-1974.

Liu FJ et al. (2013b) Investigation on structural features of Shengli lignite through oxidation under mild conditions Fuel 109:316-324.

Liu FJ et al. (2013c) Oxidation of Shengli lignite with aqueous sodium hypochlorite promoted by pretreatment with aqueous hydrogen peroxide Fuel 111:211-215.

Liu FJ, Zong ZM, Gui J, Zhu XN, Wei XY, Bai L (2018) Selective production and characterization of aromatic carboxylic acids from Xianfeng lignite-derived residue by mild oxidation in aqueous H_2O_2 solution Fuel Processing Technology 181:91-96.

Liu J et al. (2015) Mild oxidation of Xiaolongtan lignite in aqueous hydrogen peroxide-acetic anhydride Fuel 142:268-273.

Lv JH, Wei XY, Wang YH, Wang TM, Liu J, Zhang DD, Zong ZM (2016) Investigation on the structural features of Zhundong subbituminous coal through ruthenium ion-catalyzed oxidation Rsc Advances 6:11952-11958.

Lv JH, Wei XY, Zhang YY, Zong ZM (2018) Mild oxidation of Yanshan petroleum coke with aqueous sodium hypochlorite Fuel 226:658-664.

Mae K, Shindo H, Miura K (2001) A new two-step oxidative degradation method for producing valuable chemicals from low rank coals under mild conditions Energy & Fuels 15:611-617.

Miura K, Mae K, Okutsu H, Mizutani NA (1996) New oxidative degradation method for producing fatty acids in high yields and high selectivity from low-rank coals Energy & Fuels 10:1196-1201.

Murata S, Tani Y, Hiro M, Kiden K, Artok L, Nomura M, Miyake M (2001) Structural analysis of coal through RICO reaction: detailed analysis of heavy fractions Fuel 80:2099-2109.

Pan CX et al. (2013) Investigation on the macromolecular network structure of Xianfeng lignite by a new two-step depolymerization Fuel 109:49-53.

Stock LM, Wang SH (1986) Ruthenium tetroxide catalysed oxidation of coals : The formation of aliphatic and benzene carboxylic acids Fuel 65:1552-1562.

Tahmasebi A, Yu J, Yu JL, Li XC, Lucas J (2015) Solvent extraction of Chinese lignite and chemical structure changes of the residue during H₂O₂ oxidation Fuel Processing Technology 129:213-221.

Wang TM et al. (2015a) Investigation on compositional and structural features of Xianfeng lignite through sequential thermal dissolution Fuel Processing Technology 138:125-132.

Wang WH, Hou YC, Wu WZ, Niu MG (2013) Simultaneous production of small-molecule fatty acids and benzene polycarboxylic acids from lignite by alkali-oxygen oxidation Fuel

Processing Technology 112:7-11.

Wang WH, Hou YC, Wu WZ, Niu MG, Liu WN (2012) Production of Benzene Polycarboxylic Acids from Lignite by Alkali-Oxygen Oxidation Industrial & Engineering Chemistry Research 51:14994-15003.

Wang YG et al. (2015b) Oxidation of Shenmu char powder with aqueous hydrogen peroxide-acetic anhydride Fuel Processing Technology 136:56-63.

Wang YG, Wei XY, Yan HL, Liu FJ, Li P, Zong ZM (2014) Sequential oxidation of Jincheng No. 15 anthracite with aqueous sodium hypochlorite Fuel Processing Technology 125:182-189.

Wang YL, Chen XH, Ding MJ, Li JZ (2018) Oxidation of Coal Pitch by H₂O₂ under Mild Conditions Energy & Fuels 32:796-800.

Yao ZS et al. (2010) Oxidation of Shenfu Coal with RuO₄ and NaOCl Energy & Fuels 24:1801-1808.

Yu JL, Jiang Y, Tahmasebi A, Han YN, Li XC, Lucas J, Wall T (2014) Coal Oxidation under Mild Conditions: Current Status and Applications Chemical Engineering & Technology 37:1635-1644.

Figures

Figure 1

Procedure for oxidation of ZS with H₂O₂ in the presence of Fe²⁺ and GAA.

Figure 2

Total ion chromatograms of the methyl esterified products from ZS with H₂O₂ in the presence of Fe²⁺ and GAA. Reaction conditions: ZS, 1g; temperature, 60 °C; 30% H₂O₂, 20 mL; FeSO₄·7H₂O, 0.06g; oxidation time, 4 h; glacial acetic acid, 10 mL.

Figure 3

Distribution of group components in the MEE from oxidation of ZS with H₂O₂ in the presence of Fe²⁺ and GAA. Reaction conditions: ZS, 1g; temperature, 60 °C; 30% H₂O₂, 20 mL; FeSO₄·7H₂O, 0.06g; oxidation time, 4 h; glacial acetic acid, 10 mL.

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