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Effects of microwave irradiation on lignite dehydration and related wastewater characteristics

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ABSTRACT

In order to properly determine the future wastewater utilization, this study assesses the physicochemical characteristics of removed water from microwave heating of Inner Mongolia lignite with various microwave powers. The chemical oxygen demand (COD), NH_3-N, TP, pH, inorganic anions, inorganic cations and organic compounds were, respectively, analyzed. Moreover, the activated carbon, ultrafiltration membrane and NaOH solution were adopted to purify the wastewater. Results showed that microwave heating could effectively remove the lignite moisture and upgrade the coal rank. The pH of removed water was acidic and decreased with microwave power. The COD content first decreased and then increased with the peak of 509 mg/L due to the combination of organic release rate and water removal rate. All the detected cation concentrations were below 1 ppm and anion concentrations were below 10 ppm. The organic compounds in the removed water mainly consisted of polar organics, heterocyclic organics, aromatic hydrocarbons and aliphatic hydrocarbons. Therein, polar organics took up the majority, mainly alcohols and esters. The removed water quality almost got to the proper point, except for the pH and COD. After relevant purification, the acidic wastewater was neutralized and the COD contents were all below 60 mg/L, the industrial water reuse criteria.

Keywords: Wastewater; Microwave heating; Inorganic ions; Organic compounds; Purification

1. Introduction

Coal is one of the most important energy sources in the world, accounting for 29.2% of the global primary energy consumption in 2015 [1]. An estimated survey reports that 45% of the world's coal reserves consist of lignite, which is a cheap fuel with high moisture content of 25%–60% limiting its application [2]. Lignite has a low calorific value and also tends to spontaneously ignite [3]. Due to its high moisture content and spontaneous combustibility, lignite dewatering and utilization after proper processing have caused significant concerns [4–8]. Also, the reuse of removed water will be significant to the regions with abundant lignite reserve but great water shortage, such as Inner Mongolia of China [9–11]. Various drying technologies have been developed to dewater the coal, commonly thermal heating, fluidized bed drying, hydrothermal treatment and mechanical thermal expression, etc. [12–15]. However, the high energy consumption and complex process have limited their applications.

Microwaves are electromagnetic waves with wavelength ranges from 1 to 1,000 mm and frequencies from 0.3 to 300 GHz [16]. They can be transmitted, absorbed and reflected. Conventional drying systems adopt the heat

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transfer on the material surface followed by heat conduction through the particles while microwave radiation provides a volumetric and selective heating [17]. Microwaves supply energy to the coal particles and then this energy is transformed into heat within the coals by ionic conduction and dipole rotation. It affects coal samples through electric and magnetic fields while ionic and polar molecules in the coals attempt to align themselves with the oscillating electric field [18–21]. Moreover, microwave heating is an order of magnitude more efficient than thermal heating [22]. In conclusion, microwave heating has many advantages, such as improved reaction rate and yield, uniform temperature distribution, performing reaction at lower temperature and rapid temperature rise [18,19,23]. When coal samples are exposed to microwave irradiation, the moisture inside the coal will be first heated by the microware wavelength due to its polar molecule structure, while the other organic and inorganic materials keep non-thermal equilibrium state. Therefore, the moisture inside the coal sample can be selectively heated with small amount of energy [22]. The moisture will change its phase from liquid to steam with huge expansion of volume, the process will make micro-explosion and generate lots of microsteam jets to break the structure of coal particles. Hence, microwave dehydration is a promising technology to dehydrate the samples.

Extensive researches have been investigated on microwave heating [24–31]. Lester and Kingman [26] studied the effects of microwave pretreatment on grinding resistance and coal fundamental properties. They found that short exposure to microwave caused significant increase in grindability with negligible impact on the petrographic and chemical characteristics. Pickles et al. [32] discussed the effects of experiment conditions (microwave power, sample mass and initial moisture content) on drying kinetics. It was reported that microwave drying increased drying rate and lowered final moisture content. Additionally, a fitting model was obtained and activation energy was estimated. By operating a microwave oven, Tahmasebi et al. [33] observed that the drying rate increased with coal particle size, power output and decreased with coal sample mass. Meanwhile, ash content was the governing factor in the drying characteristics for samples with small particle sizes. Ge et al. [34] investigated the effects of microwave treatment on physicochemical characteristics (coal composition, pore structure, coal rank, functional groups and combustion characteristics). They concluded that the combustion processes were delayed with the increased ignition and burnout temperature due to the changed physical characteristics. Therefore, relevant reports are mainly referring to (i) improved coal utilization by microwave pretreatment (grindability, slurryability and combustion); (ii) drying kinetics and modellings of coal and (iii) physicochemical characteristic changes of coal.

Water is the essential resource for all lives to survive. Knowledge in the physicochemical properties of the water produced from microwave heating is important for determining appropriate future management strategies [35]. However, few researches have studied the characteristics of removed water by microwave upgrading not to mention the water purification.

This work adopted microwave heating to dewater the high-moisture lignite and collected the product water. The physicochemical characteristics of removed water, including chemical oxygen demand (COD), removed water amount (*R*), NH_3-N, total phosphorus (TP), pH, anions (F^-, Cl^-, SO_4^{2-}, Br^-, NO_2^-, NO_3^- and HPO_4^{2-}), cations (K^+, Ca^{2+}, Na^+, Mg^{2+}, Al^{3+}, Cu^{2+}, Fe^{2+}, Mn^{2+} and Pb^{2+}) and organic compounds, are significant to the wastewater utilization, especially in the regions with great water shortage. Furthermore, the wastewater quality was compared with selected water quality criteria and corresponding purifications were conducted. Therefore, this paper provides a novel approach for dewatering lignite and recycling the wastewater, which can be a practical guidance on lignite application and wastewater utilization.

2. Experiments and method

2.1. Coal samples

Baiyinhua lignite from Inner Mongolia (BYH) was the source of coal samples. The lignite was crushed and sieved to a particle size fraction of 0.5–2.0 mm. The result of proximate and ultimate analysis of BYH coal is listed in Table 1.

2.2. Microwave upgrading and water production processes

The heating was performed in a microwave oven with a maximum output of 2,000 W and frequency of 2,450 ± 50 MHz. In the experiment process, a quartz reactor with nitrogen gas inlet and gas outlet was placed in the middle of the microwave oven. 100 g of samples were, respectively, heated at five microwave powers (500, 600, 700, 800 and 900 W) and the microwave time was controlled to 10 min. During experiments, the nitrogen flow rate was set to 1 L/min to help the gases pass through the samples and carry out the vapors generated in the reaction. The evolved gas–vapor mixtures passed through a serpentine condenser and gas purifying filter. The liquid was collected by a condenser placed in an ice water bath. After each experiment, residual sample was taken out of the reactor and collected. Each experiment was repeated three times and the results were averaged to improve the reliability. Besides, the reached temperatures in the quartz reactor by these microwave powers were, respectively, 100°C, 130°C, 160°C, 190°C and 220°C while the interior temperatures of coal samples were much higher than these temperatures.

Table 1
Proximate and ultimate analyses of coal samples

Sample	Proximate analysis (%, ar)				$Q_{net, ar}$ (J/g)	Ultimate analysis (%, ar)				
	M	*A*	*V*	FC		C	H	N	S	O
BYH	29.47	19.27	24.64	26.62	13,400	72.88	4.49	0.90	0.82	20.91

ar = as received basis, *M* = moisture content, *A* = ash content, *V* = volatile content, FC = fixed carbon, Q_{net} = net calorific value.

2.3. Water analysis

The liquid products were basically acidic with primrose yellow color and contained plenty of organic and inorganic matters. COD, NH_3-N and TP were analyzed by a spectrophotometer (DR890, Hach, USA). The ion chromatograph (IC883, Metrohm, Switzerland) was used to measure the concentrations of F^-, Cl^-, SO_4^{2-}, Br^-, NO_2^-, NO_3^- and HPO_4^{2-}. The cation concentrations were determined by inductively coupled plasma-atomic emission spectroscopy (ICP 6300, Thermal Fisher Scientific, USA). The organics were detected by chromatograph mass spectrometer (Trace DSQII, Thermo Scientific, USA) coupled with solid-phase microextraction.

2.4. Water purification

Based on the Chinese national and industry water standards, the water removed by microwave upgrading was first absorbed by 50 g/L activated carbon with the magnetic rotator stirring for 60 min. After the absorption, the water was filtered by the 0.45 μm ultrafiltration membrane. Before filtering, the membrane was washed by deionized water to remove the impurities on the membranous layer. In the process of filtering, suction pump was used to provide the impetus. The filtration was repeated three times to deeply remove the impurities in the water. At last, 0.1 mol/L NaOH solution was adopted by burette to neutralize the acidic water.

3. Results and discussion

3.1. Properties of upgraded lignite

Table 2 shows the proximate and ultimate analyses of upgraded lignite. As the microwave power increases, the lignite moisture decreases from 29.47% to 1.79%. Marland et al. [36] reported that a 650 W microwave treatment for 8 min removed 55% moisture of a sub-bituminous UK coal while in this work, the 600 W heating for 10 min removed 69.94% moisture of an Inner Mongolia lignite, which is basically consistent with their results. Therefore, microwave upgradation can greatly remove the moisture. Meanwhile, the volatile content slightly decreases and fixed carbon content increases, which may be the results of some coal cracking and small volatile evolving out [37]. Moreover, the O/C atomic ratio decreases on the whole which allows long distance transportation and storage. The oxygen content of lignite usually comes from oxygen functional groups which will promote the spontaneous combustibility [36,37].

Fig. 1 plots the H/C atomic ratios against O/C atomic ratios which clearly presents how the H/C and O/C values change with coalification. With the microwave power increasing, the point data converges on the atomic ratios of H/C = 0.654 and O/C = 0.164. It is known that the coalification process accompanies decarboxylation and dehydration and microwave heating can effectively upgrade the lower rank coals [37]. Lignite has a high content of oxygen, which is mainly fixed in carboxyl and hydroxyl groups and the carboxyl begins to decompose even below 200°C [37].

3.2. COD, NH_3-N, TP and pH of removed water

Fig. 2(a) reveals that the pH of removed water decreases from 5.86 to 4.92 with the increased microwave power, which is similar to the acid wastewater produced by mechanical thermal expression [38,39]. The plentiful acid oxygen-functional groups in lignite, especially carboxyl and phenolic hydroxyl groups, can easily have dissociation to produce H^+ ($\text{Ar-RCOOH} \rightarrow \text{Ar-RCOO}^- + H^+$; $\text{Ar-OH} \rightarrow \text{Ar-O}^- + H^+$) [14]. As the microwave power rises, more organic acid groups were released to decrease pH. Moreover, the NH_3-N content is very low and no phosphorus is detected in the water, which indicates a relatively good water quality.

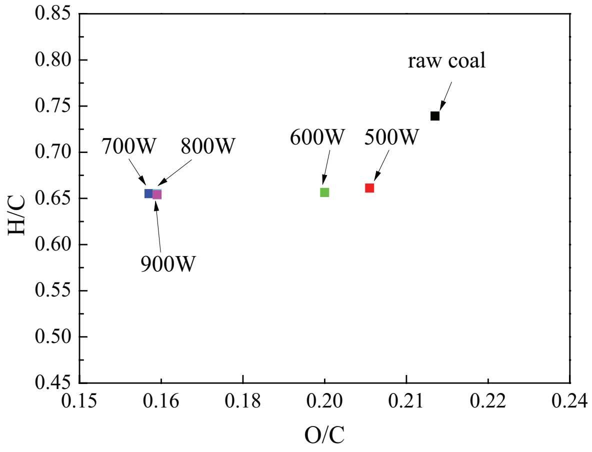

Fig. 1. The H/C atomic ratios against O/C atomic ratios of upgraded lignite.

Table 2
Proximate and ultimate analyses of upgraded lignite

Microwave power (W)	Proximate analysis (%)				$Q_{net,\,d}$ (J/g)	Ultimate analysis (%)					R (%)
	M_{ar}	A_d	V_d	FC_d		C_d	H_d	N_d	S_d	O_d	
0	29.47	27.32	34.94	37.74	21,557	52.97	3.26	0.65	0.60	15.20	0
500	12.93	28.59	33.34	38.07	20,577	52.91	2.91	0.67	0.56	14.36	56.12
600	8.86	29.18	32.50	38.32	20,933	52.78	2.88	0.76	0.66	13.74	69.94
700	5.02	30.17	31.07	38.76	21,678	53.15	2.90	1.28	0.97	11.53	82.97
800	3.02	30.56	30.40	39.04	21,595	52.91	2.89	1.29	0.72	11.53	89.75
900	1.79	30.74	29.48	39.78	21,395	52.79	2.87	1.21	0.81	11.58	93.93

ar = as received basis, d = as dry basis, M = moisture content, A = ash content. V = volatile content, FC = fixed carbon, Q_{net} = net calorific value, R (Removed water amount) = 1 – upgraded lignite moisture content/raw lignite moisture content.

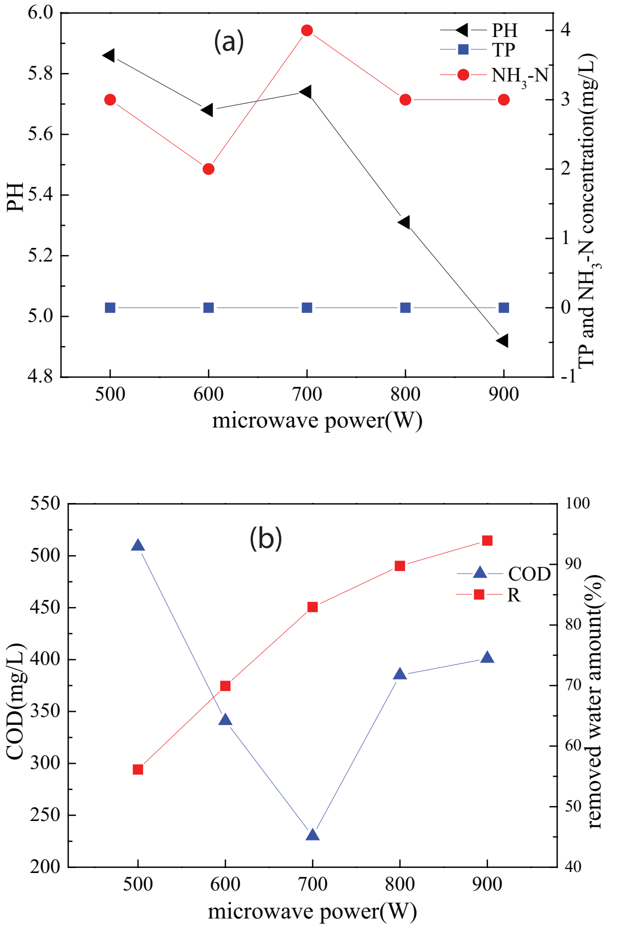

Fig. 2. Removed water quality variations with microwave power. (a) pH, TP and NH_3-N, (b) COD and *R*.

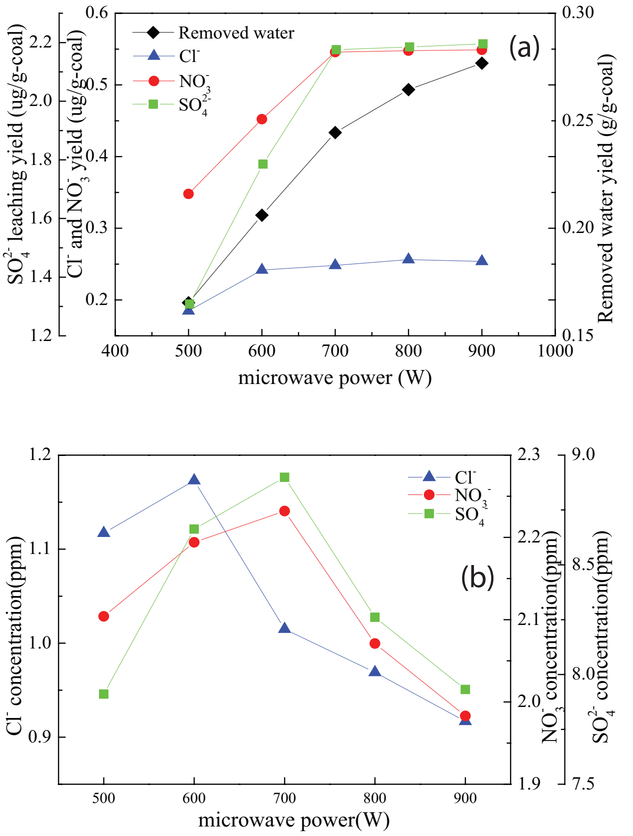

Fig. 3. Leaching characteristic of main anions in lignite upgraded by microwave process. (a) Leaching yields of main anions, (b) concentrations of main anions.

Fig. 2(b) shows that with the power increasing, the COD first decreases from 509 to 230 mg/L and then increases to 401 mg/L while the removed water amount (*R*) increases on the whole. This phenomenon of COD can be ascribed to two factors: the release rate of organics and the water removal rate. There is a balance between these two rates. In the low microwave power (500 W), the release of organic compounds was small while the removed water amount was much smaller to make a relatively high COD. As the microwave power increased (600 and 700 W), more water-soluble organic compounds were released accompanied by even more removed water [22]. Therefore, the water removal rate outweighed the organic release rate to decrease the COD. In the higher power (800 and 900 W), the removed water amount was nearly stable while the organic release kept rising to make the increased COD.

3.3. Inorganic anion characteristics in removed water

The common anions (F^-, Cl^-, SO_4^{2-}, Br^-, NO_2^-, NO_3^- and HPO_4^{2-}) in removed water were measured while Br^-, NO_2^- and HPO_4^{2-} were not detected. Fig. 3(a) exposes the leaching yields of NO_3^-, Cl^- and SO_4^{2-}. As the microwave power increases from 500 to 900 W, the yields of the three anions increase on the whole as the removed water amount does. However, it is notable that the yields of NO_3^-, Cl^- and SO_4^{2-} almost reach the constants of 0.25, 0.55 and 2.2 μg/g-coal when the power is above 700 W. And the removed water rate also slows down after the power gets to 700 W. The large amount of soluble sulphate in the lignite contributes to the high yield of SO_4^{2-}. The chlorine in the lignite can be inorganic salt-like and other organic chlorides. The organic-associated chlorine seems to predominate in coal, represented by semi-organic chlorine absorbed on the coal organic surface in pores [40]. Meanwhile, the Cl^- yield stays stable even after 600 W, which indicates it leaches out more easily than other two anions. Microwave heating takes the form of electromagnetic energy and can penetrate deeply in the sample, which allows heating to be initiated volumetrically [17,26]. Higher microwave power has a more significant effect on the formation of cracks in the coal since the power density (the volumetric absorption of microwave energy, in units of W/m^3) is proportional to the square of the electric field strength within the material [26]. Therefore, the functional groups of chloride in the lignite are much more unstable than those of sulphate and fluoride.

Fig. 3(b) shows the concentration changes of the three anions with the microwave power. When the power varies from 500 to 900 W, all the concentrations of NO_3^-, Cl^- and SO_4^{2-} first increase to the peaks (2.432, 1.173 and 8.999 ppm) and then decrease, which is the combined effects of removed water rate and anion leaching rate. When the power is low, the removed water amount is small as seen in Fig. 3(a) and some soluble salts are dissolved, leading to relatively high concentrations. As the power rises, the removed water rate reduces with the improved anion solubility due to the increased temperature, resulting in the increased concentrations. In the high power, the limited soluble anions almost leached out while the water continued to be removed. Therefore, the concentrations decreased with the power. Moreover, the Cl^- reached its peak before NO_3^- and SO_4^{2-} for its lower solubility and content, which is corresponding to the lower yield in Fig. 3(a).

3.4. Inorganic cation characteristics in removed water

Fig. 4(a) represents the leaching yields of the five common cations. It can be found that all the cation yields increase with the microwave power. The Na^+ yield is the highest, followed by Ca^{2+}, K^+ and Mg^{2+} while the Al^{3+} yield achieves the lowest. Also, the removed water amount increases on the whole with the decreased increasing rate. Optimizing the microwave treatment conditions by significantly increasing microwave power for shorter time periods could well improve any observed effects because the rate of pressure change would be remarkably higher, leading to greater stress generation [26]. It cannot be neglected that the Al^{3+} and K^+ yields level off after 600 W, indicating their low stabilities while the other three cations have relative high stabilities. Cations within the raw coal exist as dissolved salts or as weakly bonded ion-exchanged entities which can be readily removed by washing at controlled pH [39]. In the process of heating, most of the cations appear to occur as a combination of dissolved ions in pore water and exchangeable ions attached to carboxylate groups [41]. The cation yield increases with the power due to the microwave selective heating. When treated with microwaves, the moisture in the coal matrix will be heated before most of the minerals and the carbonaceous matter comes the last [26,42]. Therefore, the various thermal stresses lead to the cation dissociations in the minerals and dissolving in the removed water.

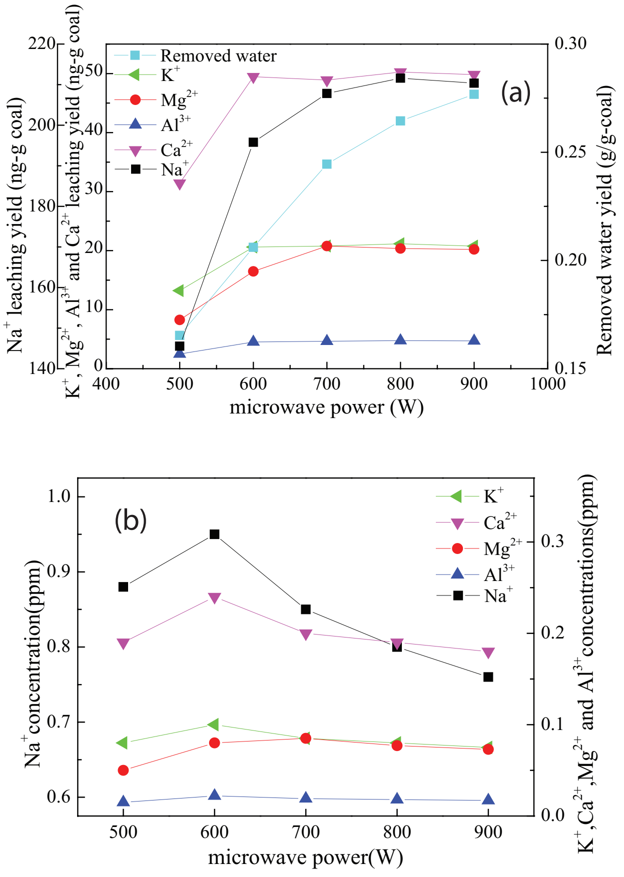

Fig. 4. Leaching characteristic of main cations in lignite upgraded by microwave process. (a) Leaching yields of main cations, (b) concentrations of main cations.

Fig. 4(b) reveals the concentration variations of the five cations with the microwave power. With the power changing from 500 to 900 W, the concentrations of K^+, Ca^{2+}, Mg^{2+}, Al^{3+} and Na^+ all first increase to the peaks (0.1, 0.24, 0.085, 0.022 and 0.95 ppm) and then decrease. It is also interesting that nearly all the cations achieve their peaks in 600 W except for Mg^{2+}. These phenomena are the results of the removed water rate and cation leaching rate. Low removed water rate and relatively high cation solubility lead to the increased concentration, as demonstrated in Fig. 3(b). Cations exchanged at carboxylic sites are unlikely to be removed except under severe conditions (it means high microwave power here) where the breakdown of the functional group occurs [38]. It is significant that Mg^{2+} and Al^{3+} concentrations get to plateau after the peaks, which indicates their high solubility and stabilization. Therefore, the monovalent species are more easily removed than multivalent cations. Some of the cations (the higher valency ones) are more slowly eluted and not merely dissolved in coal pore water, but are probably released from acid functional groups via proton-exchange with the coal [39].

The yields of the four heavy metallic cations were exhibited in Fig. 5(a). Same as the above ordinary cations, the heavy metallic yields increase with the microwave power. In the presence of mildly acidic, high temperature conditions caused by the great microwave power, may result in enhanced leaching of Cu^{2+} and some Fe^{2+} from metallic components [38]. It is noted, however, that the ion exchange behavior of Fe^{2+} is complex due to its various forms with coal (different oxidation and hydration states) [43].

Fig. 5(b) shows the concentration changes of metallic cations with microwave power. It can be seen that the metallic concentrations are all comparatively low while the highest is Fe^{2+} with the peak of 0.027 ppm. The industrial reuse standards of Fe^{2+} and Mn^{2+} are 0.3 and 0.1 ppm. Therefore, the metallic concentrations basically meet criteria for the industrial reuse. It is remarkable that the concentrations of Mn^{2+} and Pb^{2+} oppositely increased at 900 W, which may be part of the stable functional group decompositions due to the increased temperature.

3.5. Organic compounds in removed water

Table 3 presents the testing results of organics in the removed water. It can be found that the varieties of organic matters are all above 100 and increase as the microwave power rises. Increased microwave power will cause significant stress cracking and low-loss organic carbon phases will physically be heated by conduction by surrounding higher-loss phases, which are heated extremely rapidly [26].

Therein, polar organic compounds take up the majority and their carbon atom numbers are mostly between 6 and 16, mainly alcohols and esters. In addition, the varieties of heterocyclic organics come the second while the aliphatic hydrocarbons are relatively low, mainly consisting of alkenes with carbon atom numbers from 10 to 20. The varieties of aromatic hydrocarbons are a bit more than aliphatics and their benzene rings are mainly within three. Others are chain hydrocarbon derivatives containing the elements, such as fluorine, bromine, silicon, nitrogen, sulfur, phosphorus, etc. It is weird that there are so many aromatic substances in the removed water as aromatics are much more stable than aliphatics while Lin et al. [44] stated that the small aromatic molecular freely existed in the liptinite could be released from the sub-bituminous coal matrix to form light aromatics at low temperatures (even at 200°C).

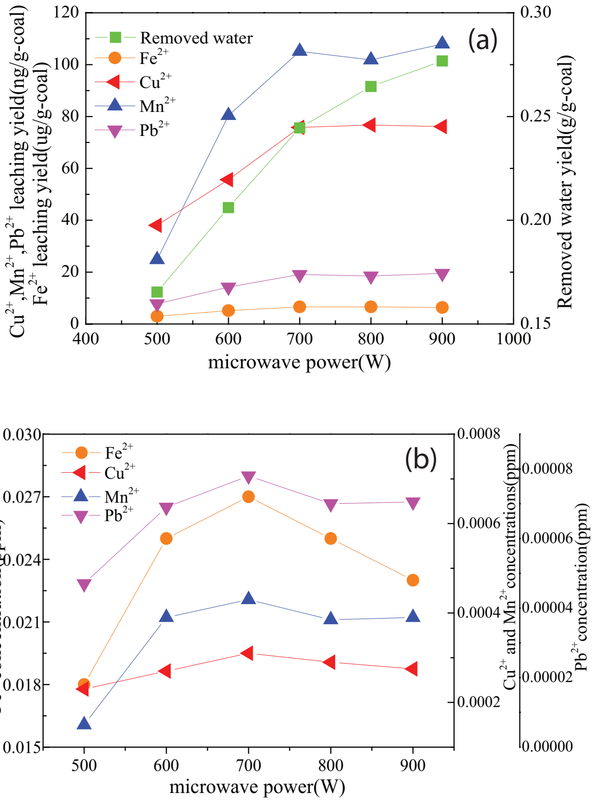

Fig. 5. Leaching characteristic of metallic cations in lignite upgraded by microwave process. (a) Leaching yields of heavy metallic cations, (b) concentrations of heavy metallic cations.

Meanwhile, the varieties of organics do not associate with their relative contents. Fig. 6 covers the relative contents of organics in the removed water, taking the total contents of the top 30 organics as a standard. It can be investigated that aromatic hydrocarbons and their derivatives occupy a considerate proportion, from 6% to 18.8% with the increasing microwave power. The detected aromatic hydrocarbons are mainly benzene and naphthalene series. Meanwhile, the benzene-alcohol and its derivatives can basically occupy more than 10% in the constitution of aromatics while they are harmful to human health and needed to be purified before industrial reuse.

3.6. Water quality assessment and purification

Comparisons of removed water qualities with the Chinese standard limitation levels are exhibited in Table 4. It can be observed that the concentrations of anions and cations all meet the requirements of Chinese water quality standards for discharge and industrial reuse. However, the pH of removed water is between 4.92 and 5.86, much lower than the discharge standard of 6.0–9.5 and reuse standard of 5.5–10.0. Also, the COD value range is within 230–509 mg/L, much higher than the limitation level of 60–200 mg/L for industrial and agricultural reuse. Therefore, pH must be improved and COD must be reduced before the water reuse.

Fig. 7 shows the COD purification by the activated carbon and ultrafiltration membrane. It is found that the absorption

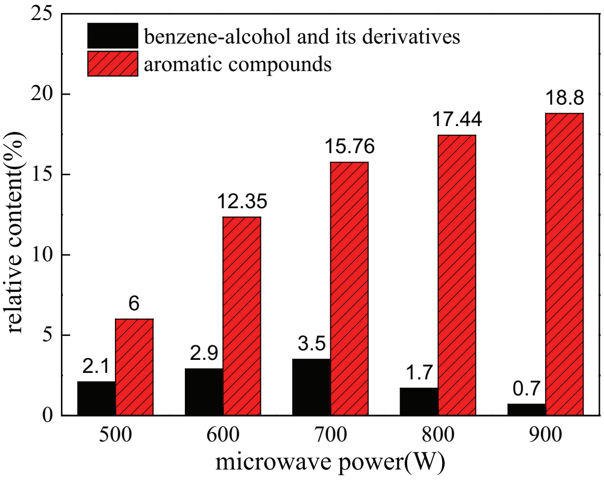

Fig. 6. The relative contents of aromatic compounds and benzene-alcohol with its derivatives.

Table 3
Varieties of organics in removed water

Microwave power	Total varieties	Aliphatic hydrocarbon	Aromatic hydrocarbon	Polar organic	Heterocyclic organic	Others
500 W	103	1	5	55	30	12
600 W	115	1	9	70	21	14
700 W	126	0	12	85	13	16
800 W	130	9	12	74	18	17
900 W	132	12	12	68	23	17

Table 4
Comparisons of removed water by microwave with Chinese water quality standards

Items	Values of removed water	Limitation levels (ppm)	
		Water discharge standards	Water reuse standards
pH	4.92–5.86	6.0–9.0[S1] 6.5–9.5[S2]	6.5–9.0[S3]; 7.0–10.0[S4]; 6.5–9.5[S5]; 5.5–8.5[S6, S7]
NH_3-N (ppm)	2–4	45	10[S3]
COD (ppm)	230–509	800[S2]	60[S3]; 200[S6, S7]
NO_3^- (ppm)	1.98–2.23	30[S2]	3[S6, S7]
Cl^- (ppm)	0.92–1.17	800[S2]	250[S3]; 700[S5]; 350[S6, S7]
SO_4^{2-} (ppm)	7.91–8.90	600[S2]	600[S3]
Ca^{2+} (ppm)	0.18–0.24	/	350[S3]; 30–500[S5]
Fe^{2+} (ppm)	0.018–0.027	10[S2]	0.3[S3]; 0.6[S4]; 0.5[S5]; 1.5[S6, S7]
Mn^{2+} (ppm)	0.00015–0.00043	5[S2]	0.1[S3]; 1.0[S6, S7]
Cu^{2+} (ppm)	0.00023–0.00031	2[S2]	1.0[S3]; 1.5[S6, S7]
Pb^{2+} (ppm)	0.000047–0.000078	1[S2]	0.05[S3]; 0.1[S6, S7]

Note: S1–S7 are national (GB) or sector (CJ,SH) standards listed as follows: S1: GB 8978-1996, Integrated Wastewater Discharge Standard; S2: CJ 343-2010, Wastewater Quality Standards for Discharge to Municipal Sewers; S3: GB/T 19923-2005, The Reuse of Urban Recycling Water – Water Quality Standard for Industrial Uses; S4: GB/T 1576-2008, Water Quality for Industrial Boilers; S5: SH 3099-2000, Water Quality Standard of Water Supply and Drainage in Petrochemical Industry; S6: GB 5084-2005, Standards for Irrigation Water; S7: GB 20922-2007, The reuse of Urban Recycling Water – Quality of Farmland Irrigation Water. The experiments were conducted at five microwave powers (500, 600, 700, 800 and 900 W) with the microwave time of 10 min.

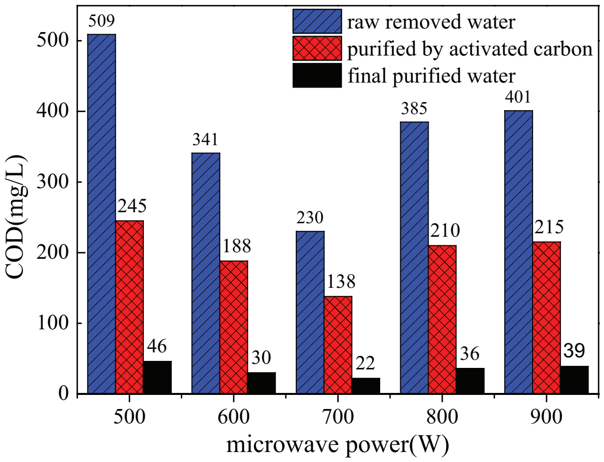

Fig. 7. COD variations with the purification process.

of activated carbon helps to reduce the COD content. All the COD contents decrease by at least 40%. The purification was carried in a mild acid environment since the dissociation and solubility of the organics in the water will be affected by H^+ and OH^-, which will influence the absorption of other solutes in the activated carbon to change the charge characteristics on the absorption surface and thereby affect the absorption capacity. After the suction filtration by the ultrafiltration membrane, the COD contents have a significant reduction and are all below 60 mg/L, the industrial water reuse criteria.

4. Conclusion

This work took advantage of microwave heating to dewater the lignite and collected the removed water. Properties of upgraded lignite and removed water were explored. Relevant wastewater purification was conducted to attain the industry water reuse criteria. The results are as follows:

Microwave heating can effectively dewater the lignite and increase coal rank. The pH of removed water is acidic while the NH_3-N content is very low and no phosphorus is detected. The COD content first decreases and then increases with the peak of 509 mg/L, due to the competitive impact of the organic release rate and water removal rate.

As the microwave power increases, all the detected cation and anion yields increase for higher temperature and pressure can generally improve the ion solubilities and dissociations. Meanwhile, all the cation concentrations are below 1 ppm and anion concentrations are below 10 ppm. Moreover, the heavy metallic cation concentrations are relatively low, below 0.03 ppm.

The varieties of organic compounds in the water are all above 100 while they mainly consist of polar organic compounds, heterocyclic organics, aromatic hydrocarbons and aliphatic hydrocarbons. Therein, polar organic compounds take up the majority, mainly alcohols and esters. The aliphatic hydrocarbons are relatively low, mainly alkenes with carbon atom numbers from 10 to 20.

Based on the relevant water reuse criteria, the removed water by microwave almost gets to the proper point, except for the pH and COD. After relevant purification, the acidic water is neutralized and the COD is below 60 mg/L.

Acknowledgments

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