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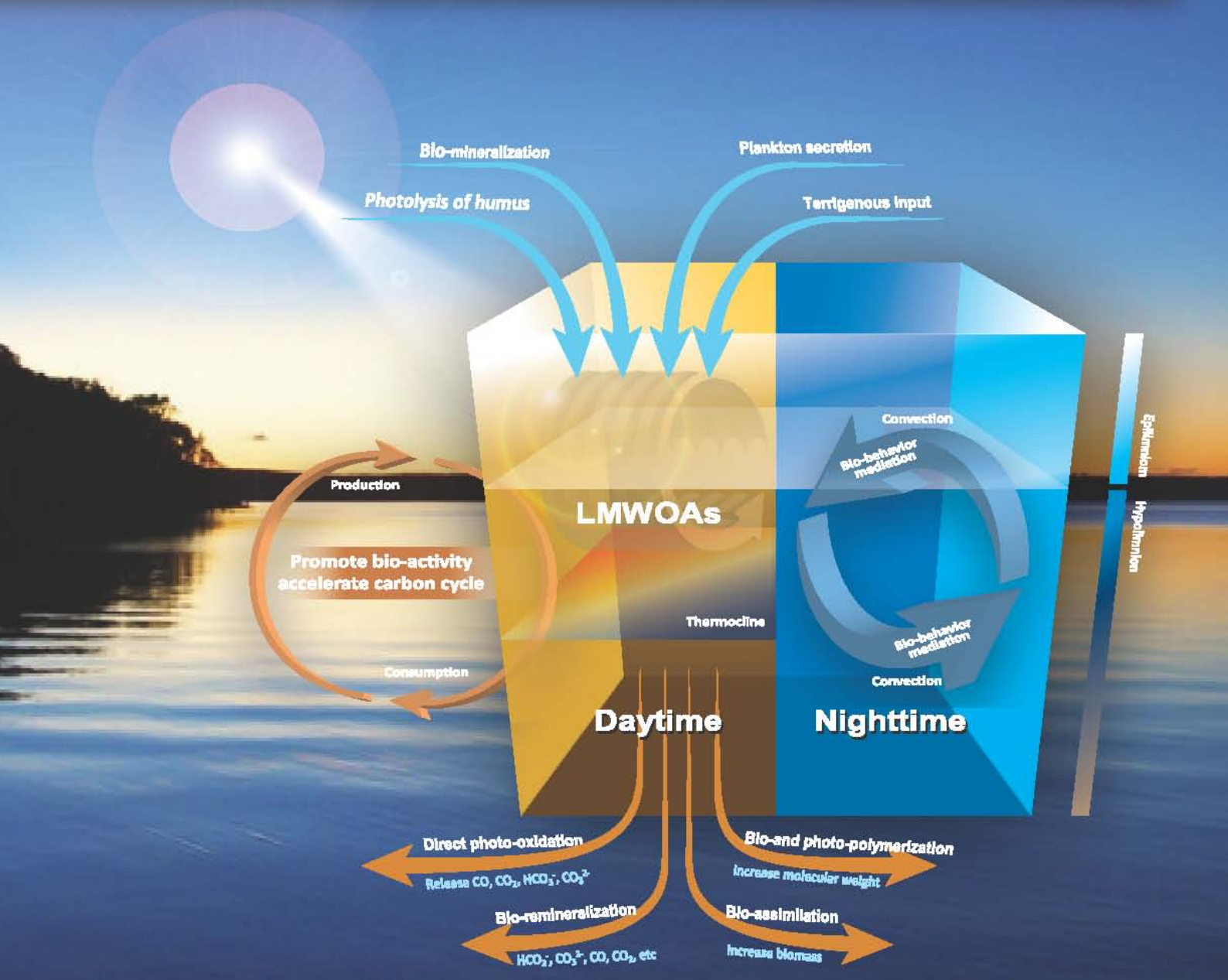

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CONTENTS

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Mercury removal from coal combustion flue gas by modified fly ash

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Abstract

Fly ash is a potential alternative to activated carbon for mercury adsorption. The effects of physicochemical properties on the mercury adsorption performance of three fly ash samples were investigated. X-ray fluorescence spectroscopy, X-ray photoelectron spectroscopy, and other methods were used to characterize the samples. Results indicate that mercury adsorption on fly ash is primarily physisorption and chemisorption. High specific surface areas and small pore diameters are beneficial to efficient mercury removal. Incompletely burned carbon is also an important factor for the improvement of mercury removal efficiency, in particular. The C–M bond, which is formed by the reaction of C and Ti, Si and other elements, may improve mercury oxidation. The samples modified with $CuBr_2$, $CuCl_2$ and $FeCl_3$ showed excellent performance for Hg removal, because the chlorine in metal chlorides acts as an oxidant that promotes the conversion of elemental mercury (Hg^0) into its oxidized form (Hg^{2+}). Cu^{2+} and Fe^{3+} can also promote Hg^0 oxidation as catalysts. HCl and O_2 promote the adsorption of Hg by modified fly ash, whereas SO_2 inhibits the Hg adsorption because of competitive adsorption for active sites. Fly ash samples modified with $CuBr_2$, $CuCl_2$ and $FeCl_3$ are therefore promising materials for controlling mercury emissions.

Key words: fly ash; mercury; modified; adsorption; flue gas
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Introduction

Mercury pollution has received considerable attention from environmental researchers due to its high volatility, long persistence, and strong bioaccumulative properties. Given that coal-fired boilers account for a significant fraction of the anthropogenic emissions of mercury into the atmosphere (Pirrone et al., 2010), researchers have actively explored the speciation and control of mercury in coal combustion flue gas. Various technologies for controlling mercury emissions from coal combustion flue gas have been investigated. Such technologies include sorbent injection and catalytic oxidation combined with wet flue gas desulfurization. However, no single technology is applied broadly. Mercury in coal combustion-derived flue gas is present in three forms: elemental mercury (Hg^0), oxidized mercury (Hg^{2+}), and particulate-bound mercury (Hg_p). Hg^{2+} is water soluble and therefore can be effectively captured by wet flue gas desulfurization systems as a co-benefit. The majority of Hg_p can be collected by electrostatic precipitators or fabric filters. Hg^0 is the most difficult to remove because of its high volatility and low solubility in water. As a representative adsorbent for Hg^0, activated carbon is frequently applied using an injection chamber, but does not yield promising results due to its high price (Pavlish et al., 2003). Fly ash has attracted more and more attention because of its lower price (Presto and Granite, 2006).

As indicated in numerous studies, the mercury adsorption properties of fly ash are closely related to the physical properties and chemical composition. The unburned carbon in fly ash plays an important role in adsorption (Wang and Wu, 2006), and the adsorption capacity differences between unburned carbon separated from fly ash and commercial activated carbon are negligible at low mercury concentrations (Wang and Chen, 2004). However, the structure of carbon differs, thus adsorption properties function in different ways (Wang and Chen, 2005). Because the composition and nature of fly ash is highly complex, its adsorption properties toward mercury are the result of the interaction of multiple factors. Nevertheless, the respective

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effects of these factors cannot be distinguished given the numerous species of elements. Adsorption mechanisms remain incompletely understood, giving rise to the need for further studies (Li et al., 2007; Maroto-Valer et al., 2005; López-Antón et al., 2009). Ferric oxides, manganese oxides, copper oxides, and other inorganic compounds enhance Hg adsorption by activated carbon because of their significant catalytic effect on Hg^0 oxidation (Bhardwaj et al., 2009; Hua et al., 2010; Shen et al., 2010; Lee et al., 2009).

Fly ash is a potential substitute for activated carbon. Inorganic compounds enhance Hg^0 oxidation, thereby improving mercury adsorption. To the best of our knowledge, this study is one of the few that focus on Hg adsorption by modified fly ash. We investigated mercury adsorption by fly ash collected from different plants, and by samples modified with metallic salts. Results show that the fly ash samples modified with $CuBr_2$, $CuCl_2$ and $FeCl_3$ exhibit excellent Hg^0 removal efficiency. On the basis of the characterization results, an adsorption mechanism is proposed.

1 Experimental

1.1 Sample preparation

The fly ash samples were collected from the electrostatic precipitators of different coal-fired plants in Hebei, Hunan, and Inner Mongolia in China, which were labeled as FA-K, FA-X and FA-Y, respectively. Modified fly ash samples were prepared by an impregnation method using the FA-K fly ash and aqueous metallic salt solutions. After impregnation at 25°C for 12 hr, the samples were dried at 110°C for 12 hr. The modified fly ash samples were marked correspondingly as metallic salt-FA, such as $CuCl_2$-FA, $FeCl_3$-FA and so on. The metallic salt loading was measured as the weight of metallic salt with respect to the support FA-K, and which was set to 14 wt.% for all the samples.

1.2 Adsorption test

The adsorption reaction was carried out in a fixed-bed quartz flow reactor at atmospheric pressure (**Fig. 1**). The reactor was a quartz tube (6 mm i.d.) with a thermocouple placed at the external wall of the reactor to control the temperature of the furnace. Fixed amounts of adsorbent mixed with quartz sand were used in all the experiments. The reactor was heated by a temperature-controlled furnace. Feed gases consisting of 6 vol.% O_2, 500 ppm SO_2, and 20 ppm HCl (when used) in N_2 were adjusted by mass flow controllers and introduced into the reactor at a total flow rate of 1 L/min. A constant quantity of 12.58 $\mu g/m^3$ of Hg^0 vapor was supplied into the gas steam, with an Hg^0 permeation tube immersed in a water bath maintained at 40°C. Analysis of Hg^0 concentrations was monitored in real time with a Lumex RA-915M Zeeman mercury analyzer (Lumex-Marketing JSC, Russia). The

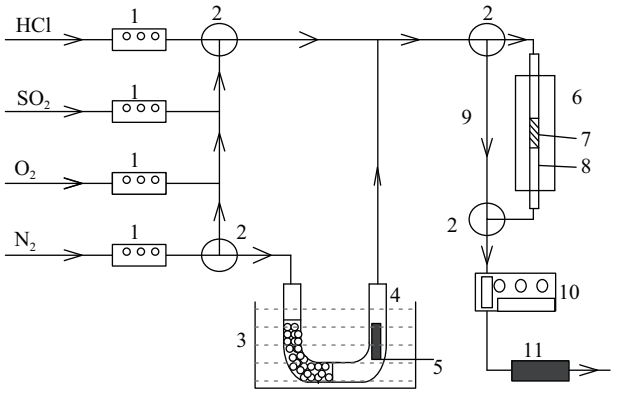

Fig. 1 Flow diagram of the experimental setup for Hg^0 removal. (1) mass flow controller; (2) three-way valve; (3) water bath; (4) U type pipe; (5) Hg^0 permeation tube; (6) fixed-bed reactor; (7) catalyst; (8) reaction tube; (9) bypass; (10) Hg analyzer; (11) exhaust gas collector.

Hg^0 removal efficiency (η, %) was quantified by the following equation:

$$\eta = (1 - \frac{C}{C_0}) \times 100\% \quad (1)$$

where, C and C_0 represent Hg^0 concentrations at the outlet and inlet of the reactor, respectively.

1.3 Sample characterization

X-ray fluorescence spectroscopy (XRF) was used to conduct composition analysis. XRF measurement was carried out on a LABCENTER XRF-1800 scanning sequence X-ray fluorescence spectrometer (Shimadzu, Japan).

The nitrogen adsorption-desorption isotherms were obtained at –196°C over the whole range of relative pressures, using a Quantachrome NOVA4000 automatic instrument (Quanta Chrome Instrument Co., USA). Specific areas and pore sizes were calculated from these isotherms by the BET and BJH methods, respectively.

X-ray photoelectron spectroscopy (XPS) was carried out on an ESCALab220i-XL spectrometer (Vacuum Generators, UK) using Al $K\alpha$ radiation ($h\nu$ = 1486.6 eV). Binding energy was corrected using adventitious carbon (284.8 eV).

2 Results and discussion

2.1 Adsorption of Hg^0 by fly ash samples

The Hg^0 removal efficiencies of the three fly ash samples were monitored as a function of time on stream at 60°C. As shown in **Fig. 2**, the FA-Y sample initially exhibited 12% Hg^0 removal efficiency. The efficiency declined to 0% after 50 min. FA-K and FA-X initially showed better activity, with 75% and 68%, respectively. Their removal efficiencies decreased to 30% and 12%, respectively, after 180 min.

The Hg^0 removal efficiency of FA-K under different adsorption temperatures was also studied, and the results

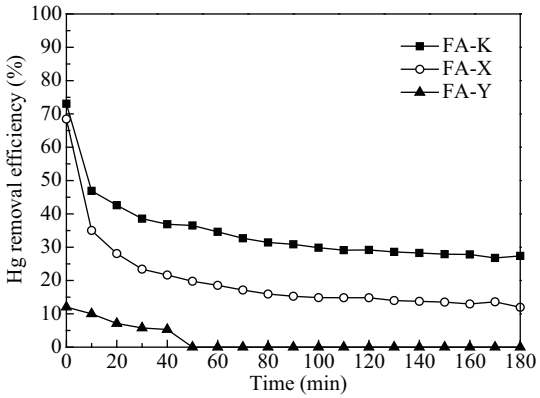

Fig. 2 Hg removal efficiency of fly ash samples (FA-K, FA-X, FA-Y). Reaction conditions: Temp. 60°C; 200 mg sorbents/l g quartz sand; flow rate 1 L/min, N_2 as balance; Hg concentration 12.58 μ/m^3. Ash samples (FA-K, FA-X, FA-Y) are referred to Section 1.1.

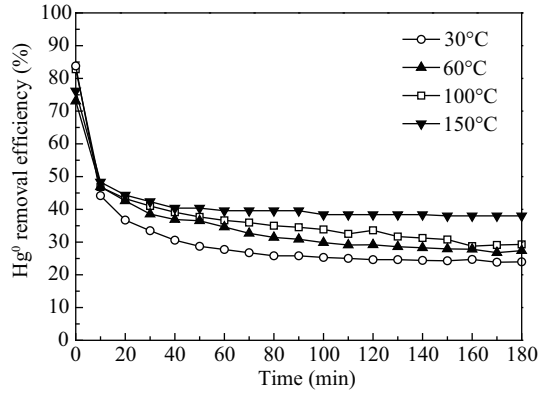

Fig. 3 Effect of temperature on the Hg^0 removal efficiency of FA-K. Reaction conditions: 200 mg sorbents/1 g quartz sand; flow rate 1 L/min; N_2 as balance; Hg concentration 12.58 μg/m^3.

are shown in **Fig. 3**. Temperature significantly affected the adsorption process. Hg^0 removal efficiency improved as temperature increased, indicating that mercury adsorption by fly ash can be attributed not only to physisorption but also to chemisorption. Because if physisorption occurs alone, removal efficiency decreases with increasing temperature.

2.2 Characterization of the fly ash samples

A composition analysis was conducted to clarify the nature of the different performance variables of the samples. The chemical compositions of the samples are summarized in **Table 1**, which indicates that the fly ash mainly contains incompletely burned carbon, SiO_2, Al_2O_3 and other metallic oxides. The fly ash samples collected from different coal-fired plants also show various concentrations of the aforementioned components. The incompletely burned carbon is a core factor in mercury adsorption by fly ash and primarily captures Hg^0 via physical adsorption (Zhao et al., 2010). Given the high carbon content, FA-K showed the best Hg^0 removal efficiency, whereas FA-Y, which had the lowest carbon content, almost failed to remove Hg^0.

Table 2 Specific surface areas and average pore diameters of the fly ash samples

Samples	FA-K	FA-X	FA-Y
BET surface areas (m^2/g)	3.96	2.39	0.50
Average pore diameters (nm)	8.42	12.75	39.50

The specific surface areas and average pore diameters of the three samples are summarized in **Table 2**. According to **Table 2**, FA-K has a large specific surface area and minimal average pore diameter. Hg^0 removal efficiency increased because of this large surface area. In addition, the atomic radius of mercury is 0.152 nm, which is far lower than the samples' average pore diameter. An appropriate aperture is generally favorable for adsorption (Gregg et al., 1989). An excessively large diameter decreases the effective specific surface area and increases the likelihood of desorption reactions. Therefore, FA-K exhibited good performance in mercury adsorption.

The samples were analyzed by XPS to identify the surface characteristics of the active species. The representative photoelectron peaks of C1s in relation to the three samples are depicted in **Fig. 4**. An essential difference in carbon properties is reflected in the behavior of the C1s lines. That is, the C1s curves of FA-K and FA-X show shoulders at high binding energies of ca. 280.9 and 281.9 eV, respectively. The FA-K and FA-X curves are assigned to the C–M bond, which is formed via the reaction of C and Si, Ti and other elements (Uhlmann et al., 1994; Seal et al., 1998; Selamat et al., 2003). The C–M bond facilitates the catalytic oxidation of Hg^0 because it can grab electrons, thereby causing an oxidation reaction (Aegerter et al., 1996; Ramanathan and Oyama, 1995). On the basis of the aforementioned results, we conclude that mercury adsorption by fly ash occurs primarily through physisorption, chemisorption and the interaction between the two.

2.3 Mercury adsorption of the fly ash modified with metal chlorides

To improve Hg removal efficiency, the fly ash was modified with a series of metal chlorides and their adsorption performance is depicted in **Fig. 5**. The modified fly ash samples

Table 1 Chemical compositions of the fly ash samples

Samples	C	SiO_2	Al_2O_3	Fe_2O_3	CaO	TiO_2	K_2O	Others
FA-K (%)	6.85	51.02	32.05	3.04	2.06	1.75	0.84	2.69
FA-X (%)	4.90	44.37	26.68	10.79	3.07	1.86	2.29	5.86
FA-Y (%)	0.62	48.81	24.10	6.17	12.71	0.87	0.82	5.91

showed better Hg removal efficiency than the unmodified samples because the chlorine in metal chlorides acts as an oxidant to promote Hg^0 oxidation. Granite et al. (2000) proposed that mercury oxidation can occur via a Mars-Maessen mechanism by which adsorbed Hg^0 reacts with a lattice oxidant such as O* or Cl*. This idea suggests that mercury oxidation can occur via a Mars-Maessen mechanism by which adsorbed or weakly bound Hg^0 reacts with Cl in chlorides. The reaction mechanism is described as follows:

$$Cl^* + Hg^0(g) \longrightarrow HgCl \quad (2)$$

$$HgCl + Cl^* \longrightarrow HgCl_2 \quad (3)$$

In addition, the metallic element of chlorides also influences the oxidation and adsorption of mercury. The activities of different chlorides follow the order: $CuCl_2$ > $FeCl_3$ > $MnCl_2$ > $CeCl_3$ > $CoCl_2$. $CuCl_2$ and $FeCl_3$ show better Hg removal efficiency. Cu^{2+} and Fe^{3+} can convert Hg^0 into Hg^{2+}, thereby facilitating the removal of Hg from the flue gas (which has strong oxidative properties). The reaction mechanism may be described as follows:

$$CuCl_2 + Hg \longrightarrow HgCl_2 + Cu \quad (4)$$

$$2FeCl_3 + Hg \longrightarrow HgCl_2 + 2FeCl_2 \quad (5)$$

2.4 Mercury adsorption of the fly ash modified with copper salt

The fly ash modified with $CuCl_2$ exhibited the best efficiency for mercury removal (**Fig. 5**). Thus the fly ash samples were modified with copper salt to investigate the effect of negative ions on mercury adsorption performance. As shown in **Fig. 6**, negative ions also influence the oxidation and adsorption of mercury. The fly ash modified with $CuBr_2$ showed better Hg removal efficiency than that modified with $CuCl_2$. The activity of different types of copper salt follows the order: $CuBr_2$ > $CuCl_2$ > $Cu(NO_3)_2$ > $CuSO_4$, which is in accordance with the literature (Wu et al., 2012; Sasmaz et al., 2012). Given that the weight ratios of different types of copper salt are the same, the difference in activity is caused primarily by the varying negative ions with different oxidation abilities.

2.5 Effect of reactant gas compositions on the activity of $FeCl_3$-FA

The fly ash modified with $FeCl_3$ also exhibited good efficiency for mercury removal (**Fig. 5**). Fe is abundant in fly ash and $FeCl_3$ is cheaper than $CuCl_2$. In addition, the Hg^0 removal efficiency of $FeCl_3$-FA under N_2 conditions enables the appropriate distinction of the effects of reactant gas on activity. Thus we chose $FeCl_3$-FA to examine the effect of reactant gas compositions on activity. The activity of $FeCl_3$-FA for Hg^0 removal under SO_2 and HCl conditions was examined (**Fig. 7**).

O_2 promotes Hg oxidation and adsorption. In the initial adsorption, Hg removal efficiency reached 100%. After 180 min, Hg removal efficiency remained at 80%, which is higher than that observed under N_2 conditions. The promotional effect of O_2 is consistent with the literature

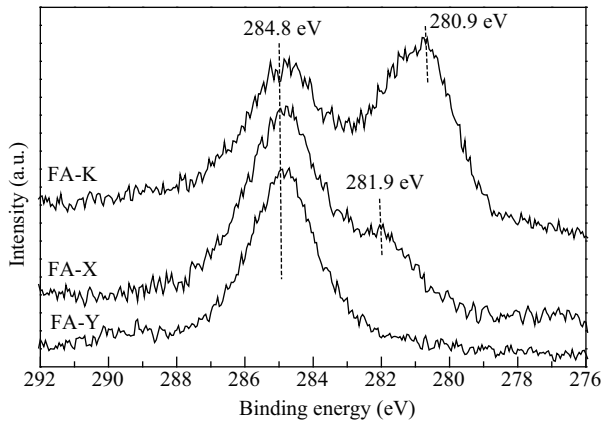

Fig. 4 Experimental C1s XPS spectra of the fly ash samples.

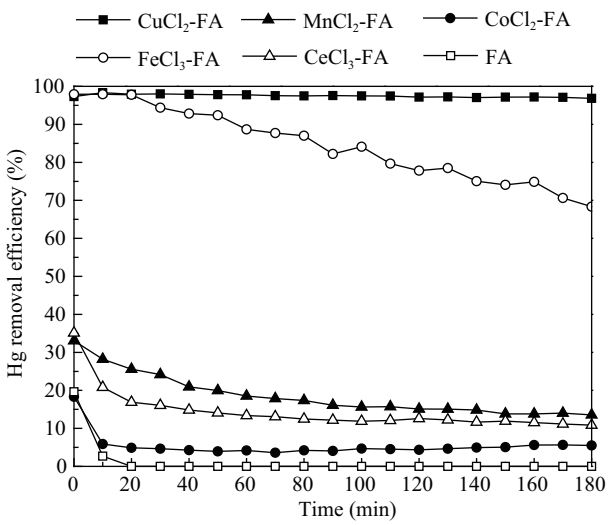

Fig. 5 Hg removal efficiency of fly ash modified with metal chlorides. Reaction conditions: temp. 100°C; 50 mg sorbents/1 g quartz sand; flow rate 1 L/min; N_2 as balance; Hg concentration 12.58 μg/m^3.

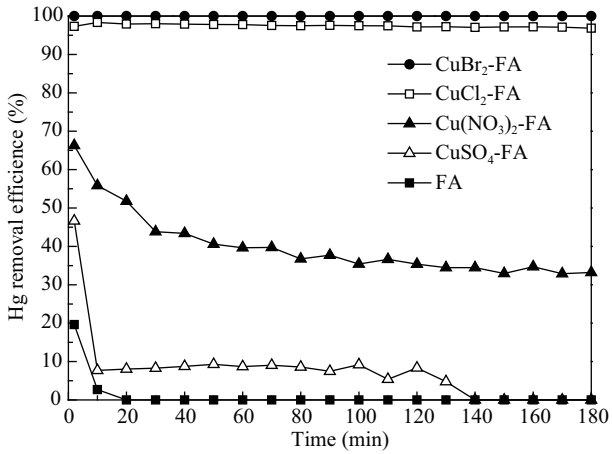

Fig. 6 Hg removal efficiency of fly ash modified with copper salt. Reaction conditions: temp. 100°C; 50 mg sorbents/1 g quartz sand; flow rate 1 L/min; N_2 as balance; Hg concentration 12.58 μg/m^3.

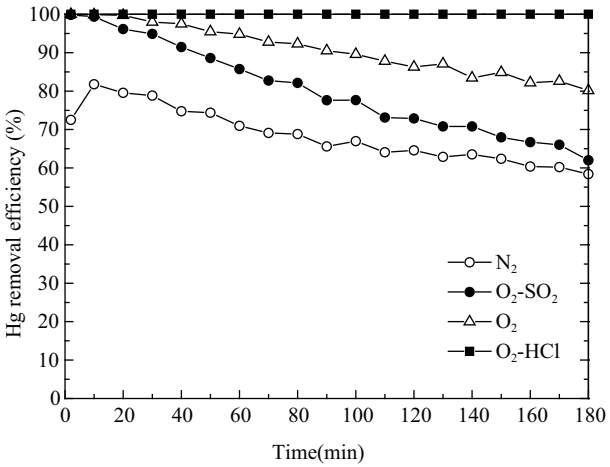

Fig. 7 Hg removal efficiency of modified $FeCl_3$-FA under different reactant gas compositions. Reaction conditions: Temp. 100°C; 50 mg sorbents/1 g quartz sand; flow rate 1 L/min; O_2 = 6%; HCl 20 ppm; SO_2 500 ppm; N_2 as balance; Hg concentration 12.58 μg/m^3.

(Granite et al., 2000; Stöhr et al., 1991; Liu et al., 2011; Yan et al., 2011; Guo et al., 2011). A similar mechanism is proposed to explain the promotional effect of O_2 in the current work, where O_2(ads) is formed through the reaction between an adsorbent and O_2(g). O_2(ads) can oxidize Hg^0 to HgO. The reaction may have occurred via the following reactions:

$$O_2(g) \longrightarrow O_2(ads) \quad (6)$$

$$Hg^0(g) \longleftrightarrow Hg^0(ads) \quad (7)$$

$$O_2(ads) + 2Hg^0(g) \longrightarrow 2HgO(g) \quad (8)$$

$$HgO(g) \longleftrightarrow HgO(ads) \quad (9)$$

Furthermore, HCl substantially promoted Hg oxidation and adsorption. During the entire 180 min, Hg removal efficiency remained at 100%. As described in Section 2.3, similar to Cl(ads) promotion of Hg oxidation and formation of $HgCl_2$, HCl was absorbed by $FeCl_3$-FA and then formed Cl under O_2 conditions. That is, Cl was replenished from gas-phase HCl. The reaction mechanism is described as follows:

$$2HCl + 1/2O_2(ads) \longrightarrow 2Cl^* + H_2O \quad (10)$$

$$Cl^* + Hg^0(g) \longrightarrow HgCl \quad (11)$$

$$HgCl + Cl^* \longrightarrow HgCl_2 \quad (12)$$

Table 3 Surface weight percentages of different C compositions on the $FeCl_3$ samples before and after reaction in N_2-O_2-SO_2 (as indicated by C1s XPS spectra)

Sample	C–C(H)	C–O	C=O	COO
Before reaction	48.05%	36.29%	6.99%	8.97%
After reaction	78.16%	14.30%	3.38%	4.08%

In addition, SO_2 is present in coal combustion flue gas; thus, the effect of SO_2 under O_2 conditions was also investigated. Unlike O_2, SO_2 negatively affected Hg removal (**Fig. 7**) possibly because SO_2 competes with Hg^0 and O_2 for adsorption active sites. To further explain the negative effect of SO_2 on Hg removal efficiency, we conducted an XPS analysis of $FeCl_3$-FA samples before and after reaction in N_2-O_2-SO_2. As shown in **Fig. 8**, the peaks at about 284.8, 286.30, 287.56, and 288.87 eV correspond to C–C(H), C–O, C=O, and COO, whose relative contents are shown in **Table 3**. C–O, C=O, and COO have oxidative properties, and their contents visibly decreased after reaction. Meanwhile, the content of C–C(H) increased. The peaks at about 198.5 eV correspond to the Cl bond to Fe^{3+} with a net charge of –1, while 200.0 eV corresponds to organic Cl. No significant difference was found between the Cl2p XPS curve of the sample before and after exposure to SO_2. The peak at 169.5 eV is consistent with the S(VI) oxidation state and is assigned to the sulfate species. The reactant gas compositions with SO_2, C–O, C=O, and COO convert Hg^0 into Hg^{2+} through oxidation, and convert into C–C(H) themselves. On the other hand SO_2 is converted into SO_3 by these oxidations. Therefore, SO_2 competes with Hg^0 on active sites, thereby negatively affecting Hg oxidation and adsorption.

3 Conclusions

Fly ash shows unique adsorption activity for mercury removal. Incompletely burned carbon is an important factor for improving mercury removal efficiency. In particular, the C–M bond, which is formed via the reaction of C and Ti, Si and other elements, may improve the oxidation of mercury. High specific surface areas and small pore diameters are beneficial for mercury removal efficiency.

Fly ash samples modified with $CuBr_2$, $CuCl_2$ and $FeCl_3$

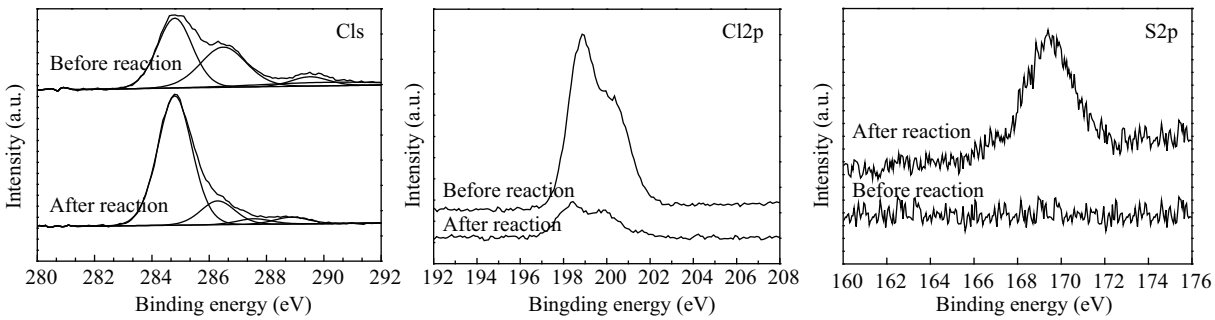

Fig. 8 C1s, Cl2p, S2p XPS spectra of $FeCl_3$-FA before and after reaction in SO_2-O_2.

showed excellent Hg removal efficiency. Mercury oxidation occurs via a Mars-Maessen mechanism, in which adsorbed Hg^0 reacts with a lattice oxidant, such as O* or Cl*, on modified fly ash. The presence of O_2 and HCl play a positive role in Hg oxidation and adsorption, whereas SO_2 inhibits Hg removal because of competitive adsorption. Modified fly ash shows promising potential for controlling mercury emissions because of its low cost and high efficiency.

Acknowledgments

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References

Aegerter P A, Quigley W W C, Simpson G J, Zieglar D D, Logan J W, Mccrea K R et al., 1996. Thiophene hydrodesulfurization over alumina-supported molybdenum carbide and nitride catalysts: adsorption sites, catalytic activities, and nature of the active surface. *Journal of Catalysis*, 164(1): 109–121.

Bhardwaj R, Chen X H, Vidic R D, 2009. Impact of fly ash composition on mercury speciation in simulated flue gas. *Journal of the Air & Waste Management Association*, 59(11): 1331–1338.

Granite E J, Pennline H W, Hargis R A, 2000. Novel sorbents for mercury removal from flue gas. *Industrial and Engineering Chemistry Researc*h, 39(4): 1020–1029.

Gregg S J, Sing K S W, 1989. Adsorption, Surface Area, and Porosity. Chemical Industry Press, Beijing.

Guo Y F, Yan N Q, Yang S J, Qu Z, Wu Z B, Liu Y et al., 2011. Conversion of elemental mercury with a novel membrane delivery catalytic oxidation system (MDCOs). *Environmental Science and Technology*, 45(2): 706–711.

Hua X Y, Zhou J S, Li Q K, Luo Z Y, Cen K F, 2010. Gas-phase elemental mercury removal by CeO_2 impregnated activated coke. *Energy Fuels*, 24(10): 5426–5431.

Lee S S, Lee J Y, Keener T C, 2009. Bench-scale studies of in-duct mercury capture using cupric chloride-impregnated carbons. *Environmental Science and Technology*, 43(8): 2957–2962.

Li M, Liu J, Zhen C G, 2007. Studies on mercury adsorption mechanism on unburned carbon surface. *Journal of Engineering Thermophysics*, 28(5): 882–884.

Liu Y, Wang Y J, Wang H Q, Wu Z B, 2011. Catalytic oxidation of gas-phase mercury over Co/TiO_2 catalysts prepared by sol-gel method. *Catalysis Communications*, 12(14): 1291–1294.

López-Antón M A, Abad-Valle P, Díaz-Somoano M, Suárez-Ruiz I, Martínez-Tarazona M R, 2009. The influence of carbon particle type in fly ashes on mercury adsorption. *Fuel*, 88(7): 1194–1200.

Maroto-Valer M M, Zhang Y Z, Granite E J, Tang Z, Pennline H W, 2005. Effect of porous structure and surface functionality on the mercury capacity of a fly ash carbon and its activated sample. *Fuel*, 84(1): 105–108.

Pavlish J H, Sondreal E A, Mann M D, Olson E S, Galbreath K C, Laudal D L et al., 2003. Status review of mercury control options for coal-fired power plants. *Fuel Processing Technology*, 82(2-3): 89–165.

Pirrone N, Cinnirella S, Feng X, Finkelman R B, Friedli H R, Leaner J et al., 2010. Global mercury emissions to the atmosphere from anthropogenic and natural sources. *Atmospheric Chemistry and Physics*, 10(13): 5951–5964.

Presto A A, Granite E J, 2006. Survey of catalysts for oxidation of mercury in flue gas. *Environmental Science and Technology*, 40(18): 5601–5609.

Ramanathan S, Oyama S T, 1995. New catalysts for hydroprocessing: transition metal carbides and nitrides. *Journal of Physical Chemistry*, 99(44): 16365–16372.

Sasmaz E, Kirchofer A, Jew A D, Saha A, Abram D, Jaramillo T F et al., 2012. Mercury chemistry on brominated activated carbon. *Fuel*, 99: 188–196.

Seal S, Barr T L, Sobczak N, Kerber S J, 1998. Microscopy and electron spectroscopic study of the interfacial chemistry in Al-Ti alloy/graphite systems. *Journal of Materials Science*, 33(16): 4147–4158.

Selamat M S, Watson L M, Baker T N, 2003. XRD and XPS studies on surface MMC layer of SiC reinforced Ti-6Al-4V alloy. *Journal of Materials Processing Technology*, 142(3): 725–737.

Shen Z M, Ma J, Mei Z J, Zhang J D, 2010. Metal chlorides loaded on activated carbon to capture elemental mercury. *Journal of Environmental Sciences*, 22(11): 1814–1819.

Stöhr B, Boehm H P, Schlögl I R, 1991. Enhancement of the catalytic activity of activated carbons in oxidation reactions by thermal treatment with ammonia or hydrogen cyanide and observation of a superoxide species as a possible intermediate. *Carbon*, 29(6): 707–720.

Uhlmann K, Harting M, Britton D T, 1994. Characterization of titanium nitride layers by positron annihilation and X-ray diffraction. *Journal of Physics: Condensed Matter*, 6(15): 2943–2948.

Wang L, Che C, 2004. Elemental mercury adsorption by residual carbon separated from fly ash. *Journal of University of Science and Technology Beijing*, 26(4): 353–356.

Wang L, Chen C, 2005. Impacts of unburned carbon fractal characteristic to its mercury sorption reaction. *Environmental Chemistry*, 24(1): 59–62.

Wang S, Wu H, 2006. Environmental-benign utilisation of fly ash as low-cost adsorbents. *Journal of Hazardous Materials*, 136(3): 482–501.

Wu J, Chen J H, Zhang S B, He P, Fang J H, Wu Y C, 2012. Removal of gas-phase elemental mercury by bromine-impregnated activated carbon. *Progress in Environmental Science and Engineering*, 356-360: 1660–1663.

Yan N Q, Chen W M, Chen J, Qu Z, Guo Y F, Yang S J et al., 2011. Significance of RuO_2 modified SCR catalyst for elemental mercury oxidation in coal-fired flue gas. *Environmental Science and Technology*, 45(13): 5725–5730.

Zhao Y C, Zhang J Y, Liu J, Diaz-Somoano M, Abad-Valle P, Martineez-Tarazone M R et al., 2010. Experimental study on fly ash capture mercury in flue gas. *Science China Technological Sciences*, 53(4): 976–983.

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