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Impact of individual acid flue gas components on mercury capture by heat-treated activated carbon*

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Abstract: Elemental mercury capture on heat-treated activated carbon (TAC) was studied using a laboratory-scale fixed bed reactor. The capability of TAC to perform Hg^0 capture under both N_2 and baseline gas atmospheres was studied and the effects of common acid gas constituents were evaluated individually to avoid complications resulting from the coexistence of multiple components. The results suggest that surface functional groups (SFGs) on activated carbon (AC) are vital to Hg^0 capture in the absence of acid gases. Meanwhile, the presence of acid gas components coupled with defective graphitic lattices on TAC plays an important role in effective Hg^0 capture. The presence of HCl, NO_2, and NO individually in basic gases markedly enhances Hg^0 capture on TAC due to the heterogeneous oxidation of Hg^0 on acidic sites created on the carbon surface and catalysis by the defective graphitic lattices on TAC. Similarly, the presence of SO_2 improves Hg^0 capture by about 20%. This improvement likely results from the deposition of sulfur groups on the AC surface and oxidation of the elemental mercury by SO_2 due to catalysis on the carbon surface. Furthermore, O_2 exhibits a synergistic effect on Hg^0 oxidation and capture when acid gases are present in the flue gases.

Key words: Flue gases, Mercury, Activated carbon (AC)
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1 Introduction

Mercury is a neurotoxin with serious bioaccumulative properties and high volatility. The generation of electricity via coal combustion has been identified as the largest anthropogenic source of mercury emission into the atmosphere (Seigneur *et al.*, 2001). Mercury emitted in flue gases is mainly in the elemental (Hg^0), oxidized (Hg^{2+}), and particulate states (Hg^P). Current air pollution control devices (APCDs) such as fabric filter (FF) bag house, electrostatic precipitator (ESP), and wet flue gas desulfurization (FGD) can remove some particulate-bound and oxidized forms of mercury (Krishnan *et al.*, 1994; Yang *et al.*, 2007). Elemental mercury, however, remains difficult to capture due to its high volatility, chemical inertness, and non-solubility in water (Chang and Offen, 1995). Strategies for mercury control have been explored extensively, including mercury oxidation upstream of wet or dry FGD and sorbent injection upstream of ESP or FF. In particular, the adsorption of Hg^0 on solid materials such as activated carbon (AC) appears to be the most promising commercial technology currently available for gas phase mercury control (Bustard *et al.*, 2004; Jones *et al.*, 2007).

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AC sorbents have been examined in all bench-, pilot-, and full-scale tests to evaluate their mercury capture efficiency in the presence of flue gases (Huggins *et al*., 2003; Ochiai *et al*., 2009). An atmosphere of pure nitrogen was used to help understand the baseline performance of the examined sorbents. Subsequently, the impacts of acid flue gas components on mercury capture were evaluated using conditions and temperatures similar to those observed in flue gases (Senior *et al*., 2000; Diamantopoulou *et al*., 2010). Although HCl and O_2 were clearly proven to increase the efficiency of Hg^0 absorption (Olson *et al*., 2000; Lee *et al*., 2004), the effect of SO_2 on Hg^0 adsorption remains unclear. Some studies have suggested that SO_2 and Hg^0 molecules occupy similar active sites on AC, which results in the inhibition of Hg^0 adsorption (Miller *et al*., 2000; Presto and Granite, 2007), whereas others asserted that SO_2 facilitates elemental mercury oxidation and enhances its adsorption on AC. Such enhancement could be attributed to the formation of new sulfur-based functional groups that provide active sites for Hg^0 on the carbon surface (Olson *et al*., 2005; Kellie *et al*., 2005).

Li *et al*. (2002) found that no Hg^0 capture was measured in baseline flue gases for carbon heat-treated at 1200 K under an inert gas atmosphere and therefore concluded that the native chemical properties of carbon sorbents played an important role in Hg^0 adsorption. Additionally, AC may contain a variety of complex chemical surface functional groups (SFGs), for example, S, Cl, carboxyl, lactone, phenol, carbonyl, pyrone, and chromene. These SFGs alone, or combined with flue gas components through a synergistic effect, can strongly affect and potentially control the oxidation and adsorption of mercury on carbon (Olson *et al*., 2000; Hu *et al*., 2009). Unfortunately, the species and quantity of SFGs can vary greatly among AC samples because of the differences in raw materials and manufacturing processes used in their production. Such variations in SFGs among AC sorbents likely explain the contradictory conclusions drawn in the literature.

Understanding Hg^0 oxidation and capture mechanisms on AC sorbents is critical to the selection and development of useful sorbents and correlative control techniques (Padak and Wilcox, 2009). In this work, SFGs on AC sorbents were removed through heat treatment under the protection of argon (Ar) and the Hg^0 adsorption behavior of heat-treated activated carbon (TAC) when subjected to various acid gases was studied using simplified conditions to investigate the mechanism of mercury adsorption.

2 Experimental

2.1 Sample preparation

Commercially available AC samples produced from coal through steam activation (purchased from Nantong Tongsen Carbon Corporation, China) were used as virgin AC in the experiments. AC samples prepared through a steam activation method, carried out at 1273–1473 K in the presence of steam, contained possible hydrogen and oxygen elements on their surfaces. The materials were subsequently ground and filtered through sieves to obtain 18–60 meshes sizes, washed with deionized (DI) water, and dried in an oven at 383 K for 24 h. To remove SFGs from the carbon surfaces, these samples were heat-treated in a quartz tube reactor under Ar at 1200 K for 10 h before they were allowed to cool to room temperature under Ar. The resulting material (denoted TAC) was stored in a desiccator prior to adsorption experiments. The mass loss, determined through weighing the samples before and after the heat treatment, was about 20%.

2.2 Fixed-bed adsorption tests

Hg^0 adsorption experiments were carried out on a simulated coal-fired flue gas adsorbing test apparatus. The schematic diagram of the experimental system is shown in Fig. 1. The system was composed of a Hg^0 vapor generation device, a gas mixing system, a fixed-bed reactor, a temperature control system, a mercury analyzer, and an exhaust cleaning system. An elemental mercury permeation tube (VICI Metronics, Inc, USA) was used for steady Hg^0 vapor generation. A certified Hg^0 permeation tube housed in a U-tube was maintained at a predetermined temperature between 313 and 343 K through submersing the U-tube in a water bath with a temperature precision of 0.1 K. The flow rate of a high-purity nitrogen (>99.99%) carrier gas was set to 300 ml/min and maintained with a mass flow controller (MFC), so that the Hg^0 vapor could be steadily injected into the fixed-bed system. The Hg^0 vapor was mixed with

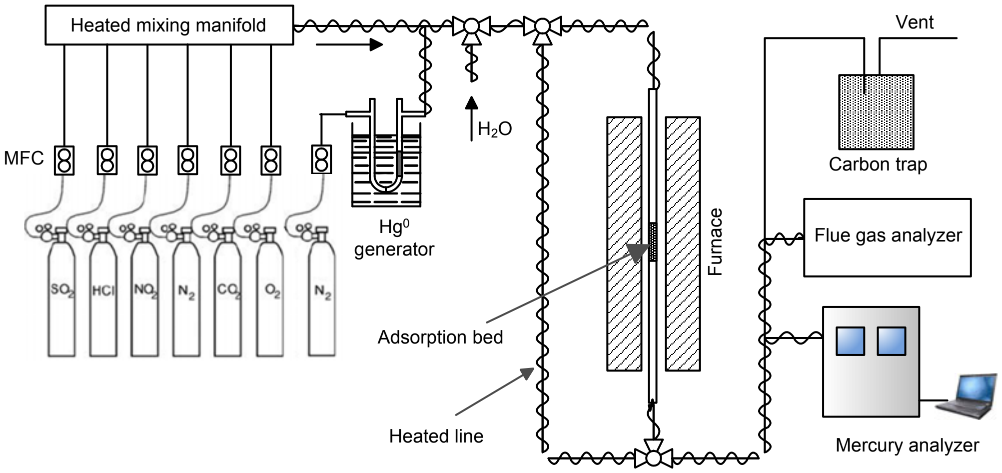

Fig. 1 Schematic diagram of the experimental unit

simulated combustion flue gases consisting of N_2, CO_2, O_2, HCl, NO, NO_2, and SO_2 at a total flow rate of 1.5 L/min. All pipes and connectors, made of Teflon, were heated to above 393 K in order to preheat the flue gas and prevent possible condensation before analysis. Hg^0 adsorption experiments were performed primarily at 393 K in a fixed-bed reactor surrounded by a temperature-controlled electrical furnace. In a typical experiment, about 50–60 mg of AC sample was supported with a quartz-fiber filter in a quartz reactor with an inner diameter of 4 mm and thickness of about 2 mm, and the Hg^0-laden simulated flue gas was fed into the reactor. The experimental conditions and compositions of the simulated flue gases are summarized in Table 1. The gas concentrations were specifically chosen to simulate the composition of a typical flue gas in the combustion of bituminous coal. A mercury continuous emission monitor (CEM, DM-6A/MS-1A, Nippon Instrument Corporation, Japan) based on cold vapor atomic adsorption spectroscopy was used to measure Hg^0 and Hg^{2+} concentrations simultaneously. A flue gas analyzer (Rosemount NGA2000 MLT, Germany) was used to continuously monitor the concentration of major flue gas components (SO_2, NO, NO_2, O_2, and CO_2). For data quality assurance, the Hg^0 concentration of inlet gas was monitored again through bypassed the adsorption bed after each experiment, and the experimental data was acceptable only when the measured value fall between 90%–110% of the concentration detected at the beginning of the test. The breakthrough rate (η) is determined by mercury concentrations at the outlet and inlet of the adsorption tube, and it is defined as

$$\eta = \frac{C_{\text{out}}}{C_{\text{in}}} \times 100\% \cdot \qquad (1)$$

Table 1 Gas concentrations used for capture tests

Gas component	Concentration
Baseline gas	
O_2	6%
CO_2	12%
Hg^0 ($\mu g/m^3$)	10–30
N_2	Balance
Acid gas	
HCl	50 ppm
NO	300 ppm
NO_2	20 ppm
SO_2	1500 ppm
Total flow rate (L/min)	1.5
Temperature (K)	393

3 Results and discussion

3.1 Characterization of adsorbents

The textural characteristics of AC were determined using a Quantasorb-1-C automated surface area and pore size analyzer, supplied by Quantachrome Instruments, USA. The characteristics of their pore structures are shown in Table 2. Both virgin AC and TAC are found to have significant micropore volumes; however, while TAC exhibits a lower multipoint Brunauer-Emmett-Teller (BET) surface area (18%) than its original AC, the total pore volume and micropore volume remain almost unchanged. To further study the AC sorbents, carbon, oxygen, hydrogen, nitrogen, and other elemental contents were analyzed using an energy dispersive spectrometer (JEM-2010, Japan) and the results are summarized in Table 2. The carbon content increases from 90.6% to 98.7% during the heat treatment process. Additionally, the contributions from oxygen, hydrogen, and others are significantly reduced, suggesting that SFGs once present on the carbon surface have been decomposed and removed from the AC surface. Figueiredo *et al.* (1999) and Mochida *et al.* (2000) also demonstrated that heat treatment decreased the number of surface groups as a result of thermal decomposition. Heating AC to temperatures around 1200 K under an inert atmosphere is an established method to remove oxygen complexes on carbon surfaces (Li *et al.*, 2003). The loss of volatile fragments and oxygen-containing groups that originally existed on AC can be observed in the mass loss of 20% and reduction of 18% in BET surface area.

Table 2 Properties of activated carbons

Activated carbon	Virgin AC	TAC
BET surface area (m^2/g)	817	692
Total pore volume (cm^3/g)	0.50	0.49
Micropore volume (<2 nm, cm^3/g)	0.21	0.19
Average pore diameter (nm)	2.61	2.73
Elemental analysis (%, in mass)		
C	90.6	98.7
O	6.4	0.3
N	1.8	0.8
H	0.9	0.1
Others	0.3	0.1

3.2 Hg^0 adsorption under N_2 and baseline gas atmospheres

Results of the Hg^0 adsorption experiments performed under N_2 are summarized in Fig. 2. In Fig. 2, virgin AC shows excellent Hg^0 adsorption capability with almost 100% capture achieved at 393 K, a temperature which is almost equal to that of authentic flue gases. The Hg^0 breakthrough curve of the TAC sorbents matches that of the blank experiment where only silicon sand particles are present in the reactor, indicating that TAC has negligible Hg^0 adsorption capability under nitrogen at temperatures from 323 to 433 K. In the adsorption curve of TAC, the Hg^0-free air in the tube between both ends of the adsorption bed was drawn at a flow rate of 0.5 L/min (required by mercury CEM) to mercury CEM when first shift to the adsorption bed, which is responsible for the initial drop in the concentration measurement. The persistence of a small amount of mercury in the adsorption bed accounts for the concentration increase during the temperature rise. Not presented in Fig. 2, TAC reveals a similar Hg^0 capture behavior under an atmosphere of baseline gases (N_2, O_2, and CO_2) to that observed with N_2. Similar results were observed in (Li *et al.*, 2003).

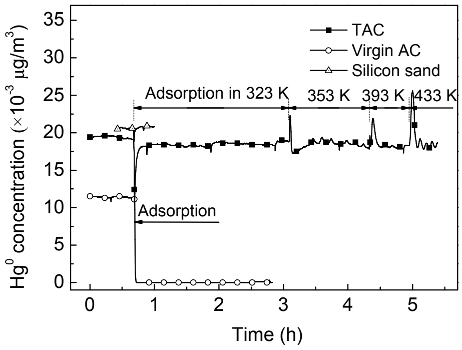

Fig. 2 Hg^0 adsorption on virgin AC, TAC, and silicon sand under an atmosphere of N_2

SFGs on carbon surfaces are almost removed through heat treatment, while changes in the measured BET area and pore structures are negligible. The disappearance of Hg^0 adsorption on TAC using baseline gases evidently suggests that Hg^0 adsorption on AC is neither based on van der Waals attraction nor simple heterogeneous chemisorption where carbon microcrystalline graphitic structures directly accept electrons from elemental mercury, a theory supported by Radovic and Bockrath (2002). Theoretical calculations recently performed by Olson *et al.* (2000) also ruled out possible direct covalent bond formation between Hg^0 and carbenium ions. These results rather suggest that SFGs on AC are vital to Hg^0 capture, although the exact species and their quantity remain unknown and may differ between carbon samples prepared with different starting materials or processing methods.

3.3 Individual Hg^0 adsorption tests with HCl, NO_2, NO, and SO_2

3.3.1 Impact of HCl

The resulting mercury breakthrough curves in the presence of 50 ppm HCl are shown in Fig. 3. As can be seen in Fig. 2 and Fig. 3, the presence of HCl greatly enhances Hg^0 capture capacity of TAC, since the mercury outlet concentration reaches only 16% of the inlet one and remains at this concentration during 2 h of the adsorption experiment under a N_2 atmosphere. This implies that 84% of Hg^0 entering the column is retained on TAC and the equilibrium time is expected to be very long. Considering that TAC shows no Hg^0 capture under baseline gases due to the lack of active sites, and that the homogeneous gas-phase interaction rate between Hg^0 and HCl is slow at low temperatures (Cao *et al.*, 2005), this significant impact of HCl on Hg^0 adsorption appears to agree well with a heterogeneous mercury oxidation mechanism. Taking into account that Hg^0 capture was enhanced dramatically after the impregnation of HCl on AC sorbents reported by Lee *et al.* (2004), we infer that the addition of HCl leads to acidic sites on TAC surfaces and the formation of mercury charge-transfer complexes, which are responsible for the Hg^0 capture. The mechanism also confirmed by Diamantopoulou *et al.* (2010) and Ghorishi *et al.* (2002).

Compared with the mercury breakthrough curve of TAC in HCl+N_2 presented in Fig. 3, the mercury outlet concentration becomes lower and remains negligible during 2 h of adsorption in the HCl+baseline experiment. The increase in Hg^0 captured on TAC demonstrates the positive impact of O_2 when HCl is included in the flue gases.

3.3.2 Impact of NO_2

The breakthrough curves presented in Fig. 4 reveal that NO_2 enhances Hg^0 capture on TAC dramatically even at a low concentration of 20 ppm. Although NO_2 is a potential Hg^0 reactant in flue gases (Hall *et al.*, 1995), kinetic limitations and the relatively short flue gas residence time in a duct or stack preclude the occurrence of homogeneous reactions involving Hg^0 and NO_2. Bench-scale test results indicate that NO_2 reacts heterogeneously with Hg^0 on fly ash or sorbent surfaces to form Hg^{2+} in simulated heated (<473 K) coal combustion flue gases (Galbreath *et al.*, 2005). The graphitic lattices in carbon particles apparently play an important role in promoting Hg^0 capture. The hexagonal carbon planes carry two prismatic edges of zig-zag and arm-chair types and the dangling bonds formed by the decomposition of the surface functional groups may preferably locate on the zig-zag edges (Mochida *et al.*, 2000). These surface defects, which are chemically unsaturated and very capable of binding certain materials/contaminants, appear to be responsible for mercury oxidation and adsorption. In the presence of NO_2, Hg^0 can be catalytically oxidized on the defective graphitic lattices to form non-volatile nitrate $Hg(NO_3)_2$ or HgO, both of which are typically bound to basic sites on the carbon surface. Capture continues until the binding sites are consumed. Similarly, Olson *et al.* (2002) demonstrated the formation of mercury nitrate on MnO_2 sorbent surfaces in the presence of NO_2. However, when SO_2 was added the mercury broke through relatively rapidly and the volatile form of mercury emitted was found to be $Hg(NO_3)_2$. It was

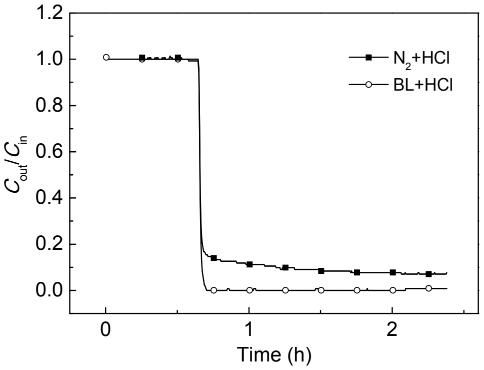

Fig. 3 Effect of HCl on Hg^0 adsorption on TAC at 393 K. BL stands for the baseline gases

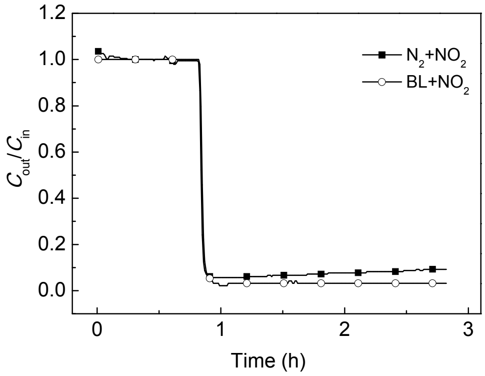

Fig. 4 Effect of NO_2 on Hg^0 adsorption on TAC at 393 K. BL stands for the baseline gases

concluded that acidic species derived from SO_2 had accumulated at the basic binding sites on the carbon that were required for binding Hg^{2+} (Olson *et al.*, 2002).

The reaction equations are listed as follows:

$$Hg^0\,(g)+NO_2\,(g)\rightarrow HgO\,(s)+NO\,(g), \quad (2)$$

$$Hg^0\,(g)+2NO_2\,(g)+O_2\,(g)\rightarrow Hg(NO_3)_2\,(s), \quad (3)$$

$$NO\,(g)+Hg^0\,(g)+O_2\,(g)\rightarrow NO_2\,(g)+HgO\,(s). \quad (4)$$

As shown in Fig. 4, the Hg^0 breakthrough rate is 6% at the beginning and increases to 9% after 2 h of adsorption under an atmosphere of NO_2+N_2, while the breakthrough rate becomes 3% and remains unchanged when subjected to NO_2+baseline gases. Such findings reveal that O_2 and NO_2 have a synergistic effect on the enhancement of Hg^0 oxidation and capture, which is in agreement with previous work (Norton *et al.*, 2003). The overall reaction mechanism can be described in Eq. (3) and Eq. (4).

3.3.3 Impact of NO

Fig. 5 shows the Hg^0 breakthrough curves of TAC under $NO+N_2$, and NO+baseline gas conditions. Also presented in Fig. 5 is the breakthrough curve of NO-impregnated TAC under a N_2 atmosphere, which was exposed to $NO+N_2$ for 1 h in the fixed bed prior to Hg^0 adsorption. Both NO and NO_2 concentrations were monitored throughout the processes and are shown in Fig. 6.

As revealed in Fig. 5, the Hg^0 capture rate on TAC under $NO+N_2$ gases is initially 50% and gradually increases to 70% within 2 h of adsorption. Compared with capture in pure N_2 (Fig. 2), the Hg^0 capture on TAC is markedly enhanced after the addition of NO. Ghorishi *et al.* (1999) also demonstrated that NO was a potent Hg^0 reactant in the presence of fly ash components. Additionally, the presence of 6% O_2 in the $NO+N_2$ gases contributes to about a 10% increase in the Hg^0 capture, indicating the favorable effect of oxygen on the oxidation and capture of Hg^0. The negligible Hg^0 escape rate under the NO+ baseline gas conditions (Fig. 5) also reflects the positive impact of oxygen on Hg^0 capture. The reactions between elemental mercury, NO, and oxygen can be catalyzed by graphitic lattices on the carbon surface and the possible mechanism is depicted in Eqs. (2)–(4) (*vide supra*).

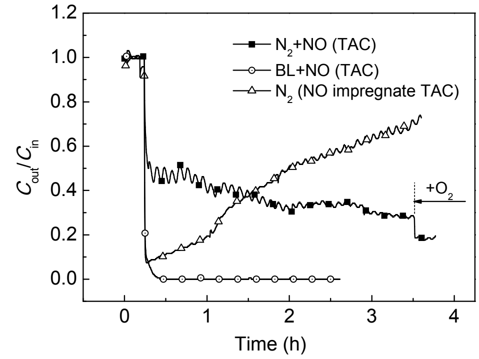

Fig. 5 Effect of NO on Hg^0 adsorption on TAC at 393 K. BL stands for the baseline gases

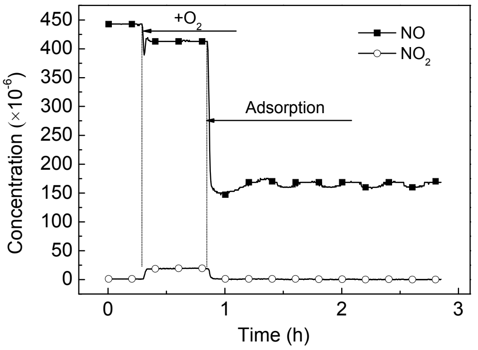

Fig. 6 NO and NO_2 concentration changes in the TAC adsorption test

In Fig. 5 it is apparent that the breakthrough rate of NO-impregnated TAC under N_2 is initially 8% and increases to 50% during 1.8 h of adsorption. Compared with the preliminary adsorption experiments performed on TAC (Fig. 2), the Hg^0 capture capacity is significantly enhanced after impregnation of NO. This can be contributed to the formation of chemisorption sites on the carbon surface due to NO impregnation, which is supported by the results of mercury X-ray absorption fine structure (XAFS) spectra, indicating that mercury is captured on sorbents only as ionic Hg^{2+} (Huggins *et al.*, 2003). As the adsorption proceeds, active sites formed through NO impregnation are filled by Hg^0 resulting in decreasing Hg^0 capture. The surface chemistry characterization of AC after NO impregnation is currently under investigation. Although NO has reportedly either promoted or inhibited mercury oxidation depending on the NO concentration (Niksa *et al.*, 2001), the presence of NO enhances the Hg^0 adsorption on TAC in the current work.

The NO and NO_2 concentrations in the synthetic gases were monitored throughout the process, from the addition of O_2 to the shift to the TAC adsorption bed under $NO+N_2$ conditions, and the results are shown in Fig. 6. The decrease in the NO concentration and increase in the NO_2 concentration upon the addition of O_2 can be explained by the reaction in Eq. (4). After $NO+N_2$ was shifted to the TAC adsorption bed, reactions occur between NO, NO_2, O_2, and elemental mercury due to catalysis on the carbon surface, resulting in concentration decreases in all NO, NO_2, and Hg^0 species.

3.3.4 Impact of SO_2

Fig. 7 shows the Hg^0 adsorption curve on TAC under an atmosphere of N_2+SO_2. Compared with that of pure N_2, the Hg^0 capture was enhanced by about 20% in the presence of SO_2. Since SFGs on AC were removed during heat treatment of the TAC samples, the possibility of elemental mercury and sulfur dioxide competition for similar active sites is minimized on the carbon surface (Serre and Silcox, 2000). A possible explanation for such enhanced mercury retention on carbon surface is the deposition of sulfur groups on the AC surface. These sulfur groups generate chemisorption sites for elemental mercury, since sulfur atoms can accept two electrons from elemental mercury and thus form oxidized Hg (Hg^{2+}) (Feng *et al.*, 2006). Additionally, the possibility of elemental mercury being oxidized by SO_2 is high under the catalysis of graphitic lattices on the carbon surface. The experimental results are highly reproducible, and the presence of SO_2 in N_2 definitely enhances Hg^0 capture on TAC. However, compared with the role of HCl, NO_2, and NO on Hg^0 adsorption, shown in Figs. 3–5, the amplifying impact of SO_2 on mercury retention is rather less intense (Fig. 7).

3.4 Impact of H_2O

Note that there was no water vapor present in simulated flue gases in the previously outlined experiments and that the presence of water has been mentioned in literature to change the adsorption characteristics of AC under some circumstances (Miller *et al.*, 2000; Li *et al.*, 2002). We have attempted to add water vapor in simulated flue gases using a peristaltic pump and an evaporator. However, large fluctuations in the mercury measurements were detected when water vapor was added leading to inconclusive results. We are striving to improve our experimental apparatus and hope to unveil the role of water in our future studies.

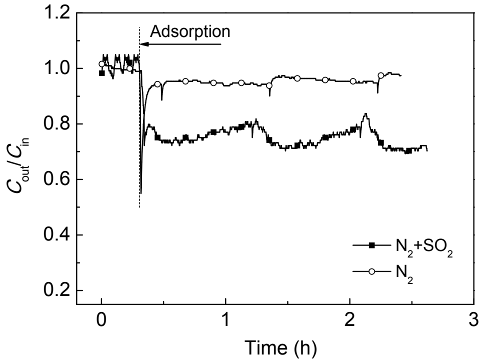

Fig. 7 Effect of SO_2 on Hg^0 adsorption on TAC at 393 K

4 Conclusions and future work

4.1 Conclusions

The Hg^0 adsorption capability is found to vanish under baseline conditions when AC samples are heat-treated at 1200 K under the protection of inert gases, although the surface area and pore volumes of these samples are still largely preserved. Such results suggest that the Hg^0 adsorption on AC is neither physisorption, nor simple heterogeneous chemisorption where carbon microcrystalline graphitic structures directly accept electrons from elemental mercury. SFGs on ACs are vital to Hg^0 capture in the absence of acid gas components although the exact species and quantity remain unknown and may differ in carbon samples prepared with different starting materials or processing methods.

The existence of defective graphitic lattices in carbon particles coupled with acid gas components plays a role in Hg^0 adsorption on TAC sorbents. The presence of HCl in baseline gases enhances Hg^0 capture on TAC markedly. A possible explanation is that the heterogeneous oxidation of elemental mercury and the subsequent formation of mercury charge-transfer complexes on the acidic sites are created on carbon surface in the presence of HCl. NO_2 and NO are also key components in the gas stream that generated a large increase in Hg^0 adsorption. In the presence of NO_2 or NO, Hg^0 is catalytically oxidized on the defective graphitic lattices of carbon surfaces and thus forms non-volatile nitrate $Hg(NO_3)_2$ or HgO, which are usually bound to basic sites on carbon. Similarly, when SO_2 is present in N_2 gas, Hg^0 capture on TAC is improved to a certain extent. The deposition of sulfur groups on the AC surface may contribute to such improvement. Additionally, elemental mercury is likely oxidized by SO_2 under the catalysis of graphitic lattices on the carbon surface. O_2 exhibits a synergistic effect on the enhancement of Hg^0 oxidation and capture when acid gases are present in baseline gases.

4.2 Future work

AC sorbents have been extensively studied to evaluate their mercury capture efficiency (Huggins *et al.*, 2003; Ochiai *et al.*, 2009) and the special roles of flue gas components, including individual acidic gas components, water vapor and the combination, have also been investigated in detail (Miller *et al.*, 2000; Lee *et al.*, 2004; Olson *et al.*, 2005). Results drawn from these sources play an important role in the development of mercury control techniques. Limited by experimental conditions and the lack of proper method and apparatus to exactly observe the surface characterization of AC samples, water vapor and multi-component experiments are not included in this paper. These preliminary results differ from previous studies since the SFGs originally existing on AC sorbents were removed through heat treatment to focus the experiments on acid gas interactions with carbon surfaces. Subsequently, Hg^0 adsorption behavior on TAC and the specific role of acid gases were studied to explore the fundamental reaction mechanisms. There has never been a more comprehensive study on this topic and the existing literature fully supports the conclusions drawn in this paper. In order to further explore the reaction mechanisms, we have submitted the application for XAFS analysis of TAC samples generated in these Hg^0 adsorption experiments to Shanghai Synchrotron Radiation Facility (SSRF, China). The effect of multiple additives in a single experiment will also be examined once basal reaction mechanisms are further explored.

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