

Hg Removal Characteristics of Noncarbon Sorbents in a Fixed-Bed Reactor

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ABSTRACT: This research targeted the development of a low-cost, high-efficiency sorbent for mercury capture in flue gas. Six non-carbon-based carriers and various impregnating substances including NaI, $CuCl_2$, $CuBr_2$, and $FeCl_3$ were investigated in this study. The performances of the prepared sorbents were tested in a bench-scale fixed-bed reactor at 140 °C in N₂ atmosphere. Some sorbents demonstrated the mercury capture capabilities similar to that of a commercial active carbon sorbent (Norit Darco LH).

1. BACKGROUND

The impact of Hg on human health has been a great public concern since the outbreak of Minamata disease. Hg in the environment is a long-term threat to ecosystems because of its neurotoxicity and enrichment along food chains.¹ With the rapid development of the power industry, Hg released from coal combustion has become one of the most important anthropogenic sources of mercury. The U.S. Environmental Protection Agency (EPA) estimated in 1997 that about one-third of the Hg released in the United States was from coal combustion.² As the world's largest coal-consuming country, China's releases of Hg from coal combustion have been estimated to increase annually. Wu et al. suggested that, from 1995 to 2003, the Hg released from coal combustion in China increased from 202 to 257 t/year.³

To reduce Hg emissions from coal-fired power plants, the U.S. EPA announced the Clean Air Mercury Rule in 2005. Although the rule was vacated by the District of Columbia Circuit Court a few years later, the U.S. EPA is now considering a new Hg control regulation under the maximum achievable control technology (MACT) scheme.⁴ The MACT limit was set as the "average emissions of the best performing 12%" of existing sources (for which emissions data are available), corresponding to over 90% Hg reduction if applied as the regulated emission limit. A new Information Collection Request aiming to determine the MACT limit for Hg and other pollutants including dioxin is now being carried out. It is expected that the new federal Hg emissions regulations for U.S. coal-fired power plants will be issued by 2015. In the meantime, many states in the United States will have state regulations in effect before the new federal regulations become available.⁴

Air pollution control devices (APCDs), including the electrostatic precipitator/fabric filter (ESP/FF) hybrid precipitator and flue gas desulfurization (FGD) devices, are capable of removing part of the Hg in flue gas. To further control the Hg discharged from power plant stacks, activated carbon injection (ACI) is considered one of the most important technologies. Halogenated active carbon sorbents have high Hg capture capabilities and have been widely tested.⁵ However, high costs and possible degradation of fly ash limit the application of

active carbon sorbents. In recent years, some researchers have suggested that modified minerals or fly ash could be attractive alternatives for Hg sorbents.^{6,7}

The most distinctive advantage of noncarbon Hg sorbents is low cost. This type of sorbent is also friendly for the cement/ concrete industry because it will not increase the carbon content in fly ash. Wendt et al. also indicated that some noncarbon sorbents can be used at elevated temperature,⁸ which would significantly increase the sorbent residence time and therefore enhance Hg capture.

Based on existing research findings, this study attempted to develop Hg sorbents from non-carbon-based materials with high specific surface areas through active substance impregnation. Two commercial active carbon sorbents were employed in this study for comparison purposes.

2. EXPERIMENTAL SECTION

2.1. Reactor System. A schematic of the fixed-bed reactor system used for Hg adsorption experiments is show in Figure 1. The apparatus is similar to one previously employed by Granite et al. to screen sorbents for mercury capture.⁹ The system consists of three parts: a Hg generator, a fixed-bed reactor, and a tail-gas treatment unit. The elemental Hg (Hg⁰) used in experiments was generated by a PSA Cavkit 10.534 mercury generator. The Hg concentration in the gas stream was monitored with Lumex RA-915+ portable mercury vapor analyzer. Before experiments, the Hg generator and analyzer were calibrated. It was verified that the readings of Lumex RA-915+ instrument fluctuated within $\pm 2\%$ of the Hg⁰ generator and analyzer.

The fixed-bed reactor itself was made of a 30-mm (insidediameter) quartz tube that could be electrically heated. The composition and flow rate of simulated flue gas were controlled by mass flow controllers (MFCs). Hg⁰ carried by N₂ was first

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Figure 1. Schematic of the fixed-bed Hg adsorption system.

heated to 140 °C in the preheating zone of the fixed-bed reactor and then passed through the sorbent bed supported by a sintered quartz disk to complete the adsorption. A thermocouple coated with quartz was inserted into the reaction zone to monitor the reaction temperature. All tubes, joints, and valves through which Hg-containing gas passed were made of either quartz or polytetrafluoroethylene (PTFE) to avoid unnecessary Hg contamination. The tail gas was treated with an active carbon trap before being released.

2.2. Experimental Procedures. Before each test, the reactor tube and downstream connections were rinsed with 10% nitric acid, deionized water, and absolute ethanol in sequence (repeated three times) and then dried. A quartz fiber filter was placed on the sintered disk to prevent disk blockage by falling sorbent. In each experiment, 0.5 g of sorbent was homogeneously mixed with 5 g of quartz sand before being placed on the filter. The bed height of sorbent/sand mixture was about 6 mm. During the each test, the Hg⁰ stream was switched on only after the reaction conditions had been attained. The Hg⁰ concentration was set at 20 μ g/Nm³, and the total flow rate was controlled at 2 L/min. Each experiment normally lasted for 1 h, during which time the Hg⁰ concentration in the gas stream after the bed was continuously measured by Lumex RA-915+ instrument. Hg captured by sorbent (Hg^p) was determined with a Milestone DMA-80 autosampler after the experiment. The oxidized Hg (Hg^{2+}) in the gas stream after the sorbent bed was deduced by subtracting Hg^p from the input Hg⁰. The overall experimental error was estimated as $\pm 15\%$. The Hg removal rate is defined as

removal rate =
$$\frac{\text{Hg}^{\text{P}}}{\text{total input Hg}^{0}} \times 100\%$$
 (1)

2.3. Sorbent Preparation. Six common non-carbon-based materials with relatively large specific surface areas were selected as the carriers in this study. The characteristics of the carriers are listed in Table 1. The characteristics of two commercial active carbon sorbents compared in this study, namely, Norit Darco FGD and Norit Darco LH (brominated), are included in the same table.

For the purposes of expression simplicity hereafter, the noncarbon carriers are abbreviated as follows: kaolinite, K; bentonite, B; zeolite, Z; calcium silicate, CS; neutral alumina, NA; and silica gel, SG.

Table	1. Ch	aracteri	stics	of l	Noncar	bon	Carriers	and
Comm	nercial	Active	Carb	on	Sorben	ts		

carrier	BET specific surface area (m^2/g)	total pore volume (cm³/g)	BET average pore size (nm)
kaolinite	9.5	5.0×10^{-2}	21.1
bentonite	27.6	6.0×10^{-2}	8.7
zeolite	79.2	4.1×10^{-1}	20.9
calcium silicate	126.7	4.2×10^{-1}	13.3
neutral alumina	145.7	2.2×10^{-1}	6.0
silica gel	342.9	9.2×10^{-1}	10.7
Norit Darco LH	405.0	4.2×10^{-1}	4.2
Norit Darco FGD	664.8	4.9×10^{-1}	2.9

It can be seen in Table 1 that the specific surface areas of noncarbon materials are smaller than those of active carbon, especially for kaolinite and bentonite. This is mainly due to the large pore size of the materials. Low-cost activation substances as listed in Table 2 were selected to modify the carriers to

 Table 2. Classifications of the Impregnated Materials and Impregnated Solution Concentrations

group	activation substance	concentration (%)
alkali metal halides	NaCl, KCl, CaCl ₂ , KBr, NaI	10
	HCl	30
transition metal halides	CuCl ₂ , CuBr ₂ , FeCl ₃ , CoCl ₂ , NiCl ₂ , CrCl ₃ , MnCl ₂ , ZnBr ₂	10
sulfur-containing compounds	Na_2S , $Na_2S_2O_3$	10
oxidizers	KMnO ₄	5
	$K_2Cr_2O_7$, $Na_2S_2O_8$	10

produce noncarbon sorbents. To prepare low-cost sorbents, the activation substances were impregnated onto the carriers from corresponding solutions. The concentrations of the impregnation solutions are also listed in Table 2.

During impregnation, 5 g of carrier was submerged into 30 mL of solution in a 50 mL plugged conical flask, magnetically stirred for 3 h, and allowed to stand for another 3 h. The prepared sorbent was filtered and rinsed three times with deionized water. The sorbent was then dried in a 105 °C oven for 12 h. The remaining solution and the rinsed water were susequently analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) to determine the amount of activation substances loaded onto carriers, defined as

$$\text{loading} = \frac{(M_{\text{original AS}} - M_{\text{remaining AS}}) \times 100\%}{(M_{\text{original AS}} - M_{\text{remaining AS}} + M_{\text{carrier}})}$$
(2)

where $M_{\rm orginal \ AS}$ is the original mass of activation substance, $M_{\rm remaining \ AS}$ is the mass of activation substances remained after impregnation, and $M_{\rm carrier}$ is the mass of carrier.

3. RESULTS AND DISCUSSION

3.1. Impregnation of Activation Substances. The loadings of different activation substances on each carrier are shown in Figure 2.

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Figure 2. Loadings of activation substances on carriers.

Among the different carriers, zeolite and calcium silicate had higher loadings of activation substances than did the others after impregnation. It was found that calcium silicate was capable of absorbing virtually all of the Cu^{2+} , Fe^{3+} , Co^{2+} , Ni^{2+} , and Cr^{3+} ions in solution. This phenomenon can be explained by ion exchange between the solutions and calcium silicate. Indeed, the Ca^{2+} concentrations in the corresponding solutions after impregnation were found to be significantly increased.

Bentonite is rather special when compared with the other carriers, because of its unique layer structure formed by fine alumina silicate grains, which provides bentonite with strong adsorption and cation-exchange abilities.¹⁰ It was found that bentonite loaded more cations than anions from solutions. The impregnation of activation substances onto bentonite is thus the joint effort of ion exchange and adsorption among layers.

3.2. Hg Removal Characteristics. *3.2.1. Carriers and Activation Substances.* To determine the Hg capture capabilities of the prepared sorbents, the Hg removals by carrier and activation substances alone were studied first, as shown in Figures 3 and 4, respectively.



Figure 3. Hg removal by noncarbon carriers.



Figure 4. Hg removal by activation substances: impregnated by (a) HCl and alkali metal halides, (b) transition metal halides, (c) sulfurcontaining compound, (d) oxidizers.

The testing results revealed that the amounts of Hg captured by all of the carriers and most of the activation substances alone were very low, much lower than those of Norit Darco sorbents. However, KMnO₄ demonstrated a moderate Hg removal rate of 56.3%. Previous research suggested that KMnO₄ is chemically unstable and might decompose to form MnO₂ during the drying process,¹¹ with which Hg could react with according to the reaction

$$2Hg + MnO_2 \rightarrow Hg_2MnO_2$$
 (3)

Apart from KMnO₄, Na₂S also exhibited some Hg capture ability, which might be caused by dissociated S^{2-} on the Na₂S surface. Although the activation substances did not show Hg capture capabilities, the Hg oxidizing capabilities of some substances (such as FeCl₃ and CuCl₂) have been confirmed by many other researchers.^{12,13}

3.2.2. Hg Capture by Noncarbon Sorbents in N_2 . The Hg removal rates of the noncarbon sorbents made from the materials listed in Tables 1 and 2 are illustrated in Figure 5. The Hg removal rates of the corresponding activation substances and active carbon sorbents are also included in the figure for comparison purposes.

The Hg removal rates of the prepared noncarbon sorbents varied dramatically from virtually nothing to almost 100%, but



Figure 5. Hg removal by noncarbon sorbent (140 °C, 20 µg/Nm³ Hg⁰, 2 L/min, N₂ balance, 1 h; AS = activation substance).

in most cases, they were much higher than the sum of the individual rates from the carrier and activation substance. It is obvious that the much improved Hg capture capabilities were contributed by the joint efforts of carrier and activation substances. The mechanisms of Hg capture by different noncarbon sorbents are discussed in detail in the following sections.

3.2.2.1. Alkali Metal Halides. HCl and alkali metal halides are often used to modify active carbon sorbents. Existing research¹²⁻¹⁴ has shown that the Hg capture capability of active carbon can be significantly improved by Cl, Br, and I ions on the sorbent surface. Hg⁰ could react with these ions to form Hg²⁺, which would be more likely to be adsorbed. Potassium iodide and other halide-promoted sorbents were studied previously, and several potential mechanisms for mercury capture were suggested.⁹

For noncarbon carriers modified by alkali metal halides, NaI performed much better than any other activation substances (Figure 5a). NaI-modified bentonite and calcium silicate achieved 88.1% and 98.6% Hg^0 removals, respectively. NaI-modified kaolinite and neutral alumina also removed more than 60% Hg^0 , comparable to the removal achieved with Norit Darco LH. It was noticed that NaI-modified sorbent became slightly brownish after impregnation. A starch test confirmed that I₂ dissociated during sorbent preparation. I₂ on the sorbent surface would chemically absorb Hg^0 to form HgI_2 , which resulted in the high Hg removal rates by NaI-modified sorbents.

From the carrier's point of view, bentonite seemed to be more adapted than others, as all of the halides improved its Hg removal after modification (Figure 5a). It might be worthwhile to point out that the chemical bonds between alkali metals and halogens are relatively strong, so that halogen–Hg⁰ reactions under these conditions are difficult. Bentonite, however, exhibiting good ion exchange and adsorption abilities because of its unique layer structure,¹⁰ might assist the release of Cl⁻ and Br⁻. These halogen ions could oxidize Hg^0 to achieve chemical capture. The captured Hg^{2+} might also be released in gas form. This type of reaction can be described by the Mars–Maessen mechanism, as follows

$$Hg^{0}(gas) + M - Cl \rightarrow HgCl(ads) + M$$
⁽⁴⁾

$$HgCl(ads) + M - Cl \rightarrow HgCl_2(ads) + M$$
 (5)

$$HgCl_2(ads) \rightarrow HgCl_2(gas)$$
 (6)

3.2.2.2. Transition Metal Halides. Among the transition metal halides, CuCl₂ and CuBr₂ seemed to be very effective, especially when modifying neutral alumina (Figure 5b). FeCl₃-modified sorbent also demonstrated a decent Hg removal rate (except for silica gel). Other active substances, such as CoCl₂ and ZnBr₂, seemed to be inadequate for modifying the carriers to achieve acceptable Hg removal rates.

Lee et al. investigated the performance of $CuCl_2$ -modified active carbon and bentonite in both fixed-bed and entrained-flow reactors.^{15,16} Their studies suggested that the Hg removal rate is directly linked to the characteristics of the carrier. $CuCl_2$ could enhance Hg oxidation and adsorption to a great extent. Their sorbent consisting of 90% $CuCl_2$ -modified bentonite and 10% Norit Darco FGD could achieve a Hg removal rate as high as 98%.

Although $CuCl_2$ and $CuBr_2$ themselves have little capability for Hg capture, their impregnation on the selected carriers resulted in high Hg removals. The findings in this study agree with the results from Lee et al.^{15,16} $CuCl_2$ and $CuBr_2$ could considerably oxidize Hg⁰; however, the fixation of Hg²⁺ on the sorbent surface is largely determined by the sorbent morphology and chemical bond strength. The reaction between $CuCl_2$ and Hg can be expressed as

$$CuCl_2 + Hg \rightarrow Cu + HgCl_2$$
 (7)

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Compared with the bentonite used by Lee et al. $(10\% \text{ CuCl}_2 \text{ loading})$, ^{15,16} the bentonite used in this study $(11.7\% \text{ CuCl}_2 \text{ loading})$ removed 63.6% of the input Hg⁰, much higher than the 10% removal rate reported. It should be noticed that bentonite is not a pure substance, but rather is often a mixture of quartz, feldspar, and calcite. Differences in morphological analysis confirmed the difference between the two types of bentonite. The impact of the composition, layer structure, and surface properties of bentonite on Hg removal will be investigated further.

Gao et al. investigated FeCl₃-modified active carbon and bentonite sorbent in a fixed-bed reactor.¹⁷ An improvement in Hg capture ability was also observed. The reaction between Hg and FeCl₃ can be expressed as

$$2\text{FeCl}_3 + \text{Hg} \rightarrow 2\text{FeCl}_2 + \text{HgCl}_2 \tag{8}$$

3.2.2.3. Sulfur-Containing Compounds. Elemental sulfur and elemental-sulfur-loaded active carbon have been confirmed to be effective in capturing Hg.¹⁸ However, research on noncarbon sorbents loaded with sulfur-containing compounds has seldom been reported. Zhang et al. investigated the Hg capture characteristics of Na₂S-loaded active carbon and found that the Hg removal rate increased, although not as high as for chlorinated active carbon.¹⁹

The effects of Na₂S, Na₂S₂O₃, and Na₂S₂O₈ were investigated in this study, as shown in Figure 5c. Na₂S itself is capable of removing 29.2% of input Hg⁰, mainly through the formation of HgS. After impregnation, however, most of the sorbents demonstrated even worse Hg removal rates than Na₂S alone (except bentonite). One possible explanation is that, during impregnation, S²⁻ lost its reactivity somehow and could no longer react with Hg⁰. The S in Na₂S₂O₃ and Na₂S₂O₈ is tightly bound by chemical bonds to its original location and is therefore inactive toward Hg. Only the Na₂S₂O₈-modified bentonite achieved a 78.9% Hg removal rate, which could be attributable to the possible radical groups formed on its surface and/or among its layer structures. More research is required to fully understand the exact Hg capture mechanism of Na₂S₂O₈modified bentonite.

3.2.2.4. Oxidizers. $KMnO_4$ as the activation substance itself is capable of removing Hg, as discussed in section 3.2.1, through reaction 3. Therefore, silica gel with a high $KMnO_4$ loading (16.8%) demonstrated an 88.4% Hg removal. Because of its unique characteristics, bentonite sorbents displayed a certain Hg capture ability, but the other sorbent's ability rarely improved upon addition of an oxidizer (Figure 5d).

3.2.3. Effect of Flue Gas Species. 3.2.3.1 H_2O . The effects of moisture in the flue gas on the Hg removal rate of noncarbon sorbents are presented in Figure 6.

 H_2O is a polar molecule capable of seizing active sites on sorbent surface. As expected, H_2O reduces the Hg removal rates to a great extent, even for active carbon sorbents. Sorbents modified by $Na_2S_2O_8$, $CoCl_2$, and $KMnO_4$ were most affected by H_2O , with their Hg removal rate being suppressed to virtually zero. Sorbent modified by $FeCl_3$ also lost more than half of their original Hg removal capabilities. The noncarbon sorbents with their Hg removal rates severely retarded by H_2O were rejected for further research because of their limited Hg capture capabilities in real flue gas.

It could be found by comparison that the sorbents with high Hg removal rates were relatively less affected by H_2O , suggesting that the effect of H_2O is somehow related to each sorbent's own reactivity.



Figure 6. Effect of H2O on Hg removal (140 °C, 20 $\mu g/Nm^3$ Hg^0, 2 L/min, N2 balance, 1 h).

3.2.3.2. HCl. Figure 7 illustrates the Hg removal rates and gaseous Hg speciation before and after HCl addition. O_2 has



Figure 7. Effect of HCl on Hg removal (140 °C, 20 μ g/Nm3 Hg⁰, 2 L/min, N₂ balance, 1 h): (a) 6% O₂ + 12% CO₂ + 8% H₂O, (b) a + 12.6 ppm HCl.

been confirmed to have little effect on Hg removal;²⁰ thus, the differences between conditions a and b in Figure 7 could be deemed as the contribution of HCl alone.

At first glance, it was surprising to discover that HCl in the gas stream actually reduced the Hg removal rates for most noncarbon sorbents, because HCl had been well accepted as an "enhancer" for Hg removal.²¹ After further examination of the percentage of Hg²⁺ in the gas stream, it was noticed that HCl indeed oxidized more Hg⁰ to Hg²⁺, especially for the NaI- and FeCl₃-modified sorbents. For Hg in the gas phase, Hg²⁺ is more likely to be absorbed by sorbent than Hg⁰. If the gas stream contains a large portion of Hg⁰ to Hg²⁺ and will consequently increase the Hg removal rate by the sorbent. This was confirmed by the experimental data for the KMnO₄-modified sorbents in Figure 7. For the cases in which gas stream mainly contains Hg²⁺, however, there is little thermodynamic space for HCl to further oxidize Hg⁰ to Hg²⁺. Under these circumstances, adding HCl to the gas phase will change part of the Hg⁰

reaction path. The newly formed Hg^{2+} is not easily adsorbed on the solid surface. There could be a kind of competition between HCl and adsorbed Hg^{2+} on the sorbent surface for adsorption sites. Already-adsorbed Hg^{2+} might be released from the sorbent surface and result in a reduced Hg removal rate.

3.2.3.3. Simulated Flue Gas. The effects of SO_2 and NO on the Hg removal rates by noncarbon sorbents were also investigated in this research. Generally, these gases were found to decrease the capability of noncarbon sorbents and increase the capability of active carbon sorbents in Hg removal. The exact reasons for this observation are still unclear, and further research is needed. The overall effects of simulated flue gas on the Hg removal rates of selected noncarbon sorbents are shown in Figure 8.



Figure 8. Effect of simulated flue gas on Hg removal (140 °C, 20 μg / Nm³ Hg⁰, 2 L/min, 1 h, 6% O₂ + 12% CO₂ + 8% H₂O + 12.6 ppm HCl + 500 ppm SO₂ + 300 ppm NO, N₂ balance).

Although affected by various gas species (H_2O , HCl, SO₂, NO, etc.) in simulated flue gas, quite a few noncarbon sorbents still demonstrated Hg removal rates higher than 40%. Neutral alumina modified by CuCl₂ seems to be the most promising sorbent, as it exhibited almost the same capability as active carbon sorbent (Norit Darco FGD).

A preliminary market survey revealed that the costs of the proposed noncarbon sorbents are only 5-30% of the costs of active carbon sorbents. The relatively low Hg removal rate of noncarbon sorbents might well be compensated by their low prices. In practice, higher Hg removal rates might be achieved by using larger doses of noncarbon sorbent, without causing any problems with high carbon content in fly ash.

It is important to point out that, apart from Hg capture capability, Hg capture speed is another important factor affecting sorbent performance in this application. Related research for noncarbon sorbents will be conducted in the next stage.

Sulfur trioxide is known to poison activated carbon sorbents for mercury capture from coal-derived flue gas.²² Future work will explore the impact of sulfur trioxide on the noncarbon sorbents investigated here.

3.2.4. Effect of Temperature. The effects of temperature on the Hg removal by noncarbon sorbents are shown in Figure 9, with the corresponding temperatures (in $^{\circ}$ C) listed in parentheses by the sorbent names.



Figure 9. Effect of temperature on Hg removal ($20 \ \mu g/Nm^3 Hg^0$, 2 L/min, 1 h, 6% O₂ + 12% CO₂ + 8% H₂O, N₂ balance).

Temperature significantly reduced the Hg removal rates of the noncarbon sorbents, even upon an increase from 140 to only 200 °C. Possible explanations could be that (i) the bonding strength between captured Hg and the sorbent surface is not great enough to resist the temperature effect and (ii) the sorbents lose their active sites to capture Hg at higher temperatures. The poor performance at high temperature requires the sorbents to be used in low-temperature regions. More detailed research needs to be conducted to study the effects of temperature (between 140 and 200 °C) and sorbent injection rate on the mercury removal rate, which would promote this technology for use before ESPs or FFs in power plants.

For sorbents modified by halides, the percentage of Hg^{2+} generally increased at elevated temperature. For this type of sorbent, a downstream wet FGD might guarantee a decent overall Hg removal rate.

4. CONCLUSIONS

The findings in this research can be summarized as follows:

- (1) Different carriers have different capacities to load activation substances. Zeolite and calcium silicate can load more activation substances than kaolinite and neutral alumina. The impregnation of calcium silicate in transition metal solution involves ion exchange, whereas the impregnation of bentonite involves ion exchange and adsorption among its layer structures.
- (2) Neither noncarbon carriers nor activation substances (except KMnO₄) have Hg capture capabilities.
- (3) Modified kaolinite and silica gel have relatively low Hg capture capabilities. Modified bentonite has a good Hg removal rate in N₂ environment. When modified by NaI, CuCl₂, CuBr₂, or FeCl₃, zeolite, calcium silicate, and neutral alumina demonstrate very high Hg removal rates.
- (4) Temperature and gas species, including H_2O and HCl, can deteriorate the Hg removal rate of noncarbon sorbents. Several combinations of carriers and activation

substances have been identified as potential sorbents in realistic simulated flue gas. Low production costs could be an important advantage for noncarbon sorbents.

This article describes some promising mercury removal sorbents. As the research has just begun, many of the reaction mechanisms require in-depth study. Moreover, secondary pollution problems caused by such removal methods need to be verified.

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Notes

The authors declare no competing financial interest.

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