Dielectric Barrier Discharge Coupling Catalytic Oxidation for Highly Efficient Hg⁰ Conversion

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ABSTRACT: In this work, we prepared CuCe/Ti catalysts in a dielectric barrier discharge (DBD) reactor and proposed a new method for flue gas mercury oxidation using DBD coupling CuCe/Ti catalyst. Our experiments verified the oxidation efficiency of flue gas Hg⁰ (ηHg⁰) and clarified the influence of O₂ content, NO concentration, SO₂ concentration, water vapor content, and discharge voltage on ηHg⁰. The oxidation mechanism of Hg⁰ in the DBD-CuCe/Ti reactor was also illustrated. The Hg⁰ oxidation experiment on the simulated flue gas (70 μg/m³ Hg⁰ + 300 mg/m³ NO + 1000 mg/m³ SO₂ + 6%O₂) with a flow rate of 1 L/min showed that when the amount of catalyst was 1.25 g and the discharge voltage was 9.5 kV, a ηHg⁰ of 93% can be achieved, which indicates that the DBD coupling CuCe/Ti technology is suitable for Hg⁰ conversion and flue gas mercury removal.

1. INTRODUCTION

The mercury in the environment can be divided into naturally released mercury and human released mercury. Eighty percent of the mercury in the atmosphere is in the form of vapor, and mainly from the burning of fossil fuels. Gaseous mercury is mercury that can pass through a 0.45 μm pore filter membrane or other filtering devices. It has the characteristics of long retention time, so it can not only carry out the long-distance transmission but also participate in the global mercury cycle, form particles, and settle in situ. China is the world’s largest coal consumer. The average mercury content (approximately 0.15–0.20 μg/g) of coal in China is higher than the world averaged content (0.13 μg/g), thus the mercury pollution problem in China is more serious.¹⁻⁴

The Hg in coal mainly exists in the form of mercury–sulfur bonds. When the boiler burns at high temperatures, the mercury–sulfur bond breaks, and most of the Hg enters into the flue gas in the form of gaseous element mercury Hg⁰, which may be chlorinated or oxidized to form HgCl²⁻ or be catalytically oxidized on the surface of fly ash. Gaseous Hg⁰ is adsorbed on the surface of fly ash to form particulate mercury Hgₚ.⁵⁻⁶ At present, there are three ways to remove mercury after combustion. One is to modify the existing flue gas purification equipment to achieve the combined removal of multiple pollutants and improve the removal efficiency; the other is to add absorbents to the tail flue gas to remove Hg; the third is to use a catalyst to oxidize Hg in the flue gas to ease its removal.⁷⁻¹⁰ For example, selective catalytic reduction (SCR) technology can oxidize Hg⁰ to HgCl²⁻ and the conversion rate reaches 30–80%.¹¹ The generated HgCl²⁻ and particulate mercury Hgₚ can be further removed by electrostatic precipitator (ESP) or bag filter and wet desulfurization unit. However, these traditional mercury removal methods have too long and complicated processes, numerous equipment, and a large area occupation, and the operation and equipment maintenance costs are too high.¹² Therefore, the development of new technologies and the use of as few equipment as possible to efficiently remove multiple pollutants in a relatively short process are important development directions for flue gas purification.¹⁰,¹³

Hg⁰ has a low melting point and is not easily soluble in water, acid, and alkali. Therefore, the removal of Hg⁰ depends on its efficient and quick oxidation of Hg⁰ to HgCl²⁻, which is easily removed.¹⁴ The use of nonthermal plasma (NTP) to treat the catalyst and then coordinate Hg⁰ removal will be one of the new development trends of flue gas Hg⁰ removal in the future. Compared with the traditional Hg⁰ removal technology, this method can not only save the cost of the precious metal catalyst but also efficiently remove a variety of pollutants in the flue gas. Moreover, it has a small equipment area, simple procedures, operation convenience, and other advantages.¹⁵

NTP uses corona discharge to generate *O and *OH free radical particles and O₃, which has a good effect on the...
et al.32 and Zhou et al.33 showed that the DBD coupling role of the catalyst is very critical.20,21 Commonly used promote the conversion of pollutants. In this approach, the approaches because it can increase the reaction rate and process. Catalytic oxidation is one of the commonly used application of NTP technology in the pollutant removal other approaches must be combined to promote the conversion of pollutants. In this approach, the role of the catalyst is very critical.20,21 Commonly used catalysts include precious metals, transition-metal oxides, activated carbon, and molecular sieves. In recent years, catalysts loading transition-metal oxides such as iron, copper, manganese, cobalt, and cerium have been extensively studied.22,23 An et al.24 prepared a 3% CeO2−WO3/TiO2 catalyst and found that the oxidation efficiency of Hg0 (ηHg) can reach 86.6% after combining with NTP. Plasma technology has the advantage of the ability to produce nanostructured catalysts, low energy consumption, environmentally friendly properties, ability to use a wide range of substrates, and a high degree of universality in catalyst preparation compared with calcination.25,26 Liu et al.12 and Huang et al.27 showed that the catalyst with good performance could be prepared in a dielectric barrier discharge (DBD) reactor. When the catalyst is filled in the discharge area of DBD, the performance of the catalyst can be further improved in the discharge process of DBD.28 Our previous work29−31 showed that DBD combined with the catalyst can effectively promote simultaneous oxidation. Zhang et al.32 and Zhou et al.33 showed that the DBD coupling catalyst can significantly improve ηHg. Previous studies34−36 have also shown that, compared with other metal oxides, Cu oxide has a strong ability to oxidize Hg0, while Ce oxide has good oxygen storage capacity. Titanium dioxide (TiO2) is rich in resources, has low cost, has stable chemical properties, and resistant to acid and alkali corrosion, thus it is often used as a synthetic material for commercial catalysts. It can be expected that the TiO2 catalyst loaded with Cu oxide and Ce oxide has a good oxidation ability for Hg0. Therefore, the combination of DBD-CuCe/Ti catalyst is worthy of further study.34−36

Figure 1. Experimental system schematic.

The main contents of this work are as follows: (1) use DBD reactor to prepare a CuCe/Ti catalyst suitable for Hg0 oxidation and perform X-ray diffraction (XRD) pattern analysis, X-ray photoelectron (XPS) energy spectrum analysis, and scanning electron microscopy (SEM) analysis; (2) determine the oxidation and conversion efficiency of Hg0 by the DBD-CuCe/Ti reactor and show the influence of O2 content, NO concentration, SO2 concentration, and water vapor content on ηHg; and (3) clarify the oxidation mechanism in the DBD-CuCe/Ti reactor.

2. EXPERIMENTAL SECTION

2.1. Chemicals and Materials. Cerium nitrate solution (Ce(NO3)3·6H2O) and copper nitrate (Cu(NO3)2·3H2O) were of AR grade and purchased from Shanghai Macklin Biochemical Co., Ltd. Titanium dioxide (TiO2, P25) was purchased from Degussa. All chemicals were used as received without further purification. The deionized water used in the experiment was prepared with an ultrapure system. High-purity N2, high-purity O2, 5% NO/N2, and 5% SO2/N2 were used as plasma-catalytic reaction reactants.

2.2. Catalyst Preparation. Using TiO2 (Degussa P25) as a carrier, the required catalyst was prepared by the impregnation method. To prepare Cu/Ti (mass ratio Cu/TiO2 = 0.1), Ce/Ti (mass ratio Ce/TiO2 = 0.1), and CuCe/Ti (molar ratio Cu/Ce = 1:1, mass ratio (Cu + Ce)/TiO2 = 0.1) catalysts, Cu(NO3)2·3H2O and Ce(NO3)3·6H2O were needed. First, certain amounts of cerium nitrate and copper nitrate were dissolved in deionized water then the dried TiO2 (Degussa P25) powder was added into the solution. The mixture was stirred using a thermostatic magnetic stirrer (DF101S, Yuhua Instrument Company, Gongyi) for 30 min. Subsequently, the sample was sonicated with an ultrasonic oscillator (PS-30T, Kangjie Electric Appliance Company, Shenzhen) for 30 min. Finally, the catalyst precursor was packed in the sealed discharge area of the DBD reactor, then N2 and O2 were passed into the reactor through a gas distribution system. DBD discharged the catalyst precursor under N2−O2 atmosphere to prepare the required catalyst.
2.3. Catalyst Characterization. The crystal morphology of the catalyst was determined by an X-ray diffractometer (D8, Bruker, Germany). The diffractometer used Cu Kα (λ = 0.1542 nm) as the radiation source, with a diffraction angle of 20 ranging from 10 to 90° and a resolution of 0.02°. The results were analyzed by MDI Jade 6.0 software. X-ray photoelectron spectroscopy (XPS) analysis was performed on an electron spectrometer (ESCALAB 250 Xi, Thermo Scientific). All binding energies were calibrated by the C 1s line of 284.6 eV. The relative content of the elements on the catalyst surface was deduced by analysis and fitting of the Gaussian–Lorentzian curves using XPS PEAK software. Scanning electron microscopy (SEM) images were taken on a JEOL JSM-7500F instrument equipped with an OXFORD energy-dispersive spectrometer at an acceleration voltage.

2.4. Experimental Setup. The system shown in Figure 1 can be used to prepare the catalysts and oxidize pollutants. The whole system is divided into the gas distribution system, DBD reactor, discharge control and monitoring system, analysis and test system, and exhaust gas treatment system. The simulated flue gas was prepared by the gas distribution system, and the N2, NO, SO2, and O2 gases were mixed according to the required concentration under the control of the flowmeter. H2O(g) was produced by a water vapor generator. The mercury permeation tube was placed in a U-shaped glass tube filled with glass beads, which ensured uniform heating of the mercury permeation tube and a uniform gas flow. The U-shaped tube was heated in a water bath at a constant temperature (50 °C) to ensure a stable amount of elemental mercury (70 μg/m3). The catalyst (1.25 g) was placed in the discharge space of the DBD reactor and fixed by quartz wool. The flow rate of the inlet flue gas was 1 L/min. The reacted gas was analyzed by a mercury analyzer and a flue gas analyzer and finally emptied after being absorbed by an exhaust gas treatment device.

3. RESULTS AND DISCUSSION

3.1. XRD, XPS, and SEM Analysis. The XRD patterns of the Cu/Ti, Ce/Ti, and CuCe/Ti catalysts are shown in Figure 2. The observed characteristic peaks of CuO/Cu2O (Cu/Ti catalyst), CeO2 (Ce/Ti catalyst), CuO/Cu2O/CeO2 (CuCe/Ti catalyst) indicated that the CuCe/Ti catalyst had a higher dispersion of Cu and Ce oxides. Moreover, the crystallinity of Cu and Ce oxides in the CuCe/Ti catalyst was lower. A study showed that the active component oxide with low crystallinity is more favorable for the catalytic reaction. Therefore, the catalytic oxidation activity of the catalyst containing CuCe may be higher.

The photoelectron spectra of Cu 2p, Ce 3d, O 1s, and Ti 2p are shown in Figure 3. From Figure 3a, it can be observed that Cu2+/(Cu2+ + Cu+) in Cu/Ti and CuCe/Ti were 70.6% and 76.2%, respectively. Cu2+ is an active site, which can strengthen the oxidation of Hg0, thereby promoting the catalytic oxidation under low-temperature conditions. The proportions of Ce3+/(Ce3+ + Ce4+) in Cu/Ti and in CuCe/Ti obtained from Figure 3b are 28.3 and 31.1%, respectively. The doped Cu and Ce may decrease the energy required for the formation of oxygen vacancies on the catalyst surface, increasing Ce3+/(Ce3+ + Ce4+), which is conducive to the formation of chemisorbed oxygen. From Figure 3c, one can calculate that O2/(O + O3) in CuCe/Ti is 25.4%, while these values in Ce/Ti and Cu/Ti are 15.3 and 16.9%, respectively. Therefore, CuCe/Ti may have higher catalytic activity in the catalytic oxidation of Hg0. It can be calculated from Figure 3d that the values of Ti3+/Ti4+ in Ce/Ti, Cu/Ti, and CuCe/Ti are 68.6, 70.6, and 77.2%, respectively. As active O species have mainly resulted from the conversion of Ti3+ to Ti4+, one concludes that among the three catalysts, the CuCe/Ti catalyst may have the highest catalytic activity.

The surface morphology in Figure 4 shows that the surfaces of Cu/Ti and Ce/Ti catalysts are loose, the regularity of morphology is poor, and the particle size distribution is not uniform enough; however, the CuCe/Ti catalyst has a smoother surface and more uniform particle size distribution. The above three characterization results indicated that CuCe/Ti may have better catalytic performance.

3.2. Effects of O2 Content and Discharge Voltage on ηHg. The energy density can be calculated by SED (J/L) = P (J/s)/Q (L/min) × 60 s/min, in which P represents the power consumed and Q represents the flow of gas. We recorded the voltage and current data from the oscilloscope. The relationship between energy density and voltage thus obtained is shown in Figure 5, indicating that when the voltage increased from 3 to 7.5 kV, SED increased rapidly from 38.1 to 48.5 J/L. When the voltage was increased from the range of 8–10 kV, SED increased rapidly from 38.1 to 48.5 J/L. When the voltage was further increased, SED increased faster.

O3 and free radicals are produced during the DBD discharge, as shown in eqs 1–4. Figure 6 shows the effect of the O3 content on the ηHg at different discharge voltages. In the range of 3–8 kV, the variation of the Hg0 content was very small, so it is not plotted in Figure 6.

The reason for this can be explained in Figure 5. When the voltage was less than 8 kV, the change in energy density was small, so the number of generated free radicals was small and the ηHg low. When the voltage was greater than 8 kV, the energy density increased rapidly as the voltage increased, and the ηHg also increased rapidly. When the discharge voltage was constant, the higher the O2 content, the higher the collision probability of O2 and higher the energy of the electrons, thus more O3 and *O were generated to participate in the reaction, and the ηHg was increased. For the four kinds of O3 contents,
the $\eta_{Hg}$ reached the maximum (85.1, 90.7, 93.5, and 96.5%, respectively) in the range of 9.5−10 kV. In the case of too high voltage, because $N_2$ in the flue gas as the carrier gas and its content far exceeds $O_2$, a large amount of $^*N$ produced by high-voltage discharge would preferentially consume $O_3$ and $^*O$, resulting in a decrease in the $\eta_{Hg}$. Moreover, in the case of

Figure 3. X-ray photoelectron energy spectrum analysis of the catalysts: (a) Cu 2p, (b) Ce 3d, (c) O 1s, and (d) Ti 2p.

Figure 4. Scanning electron microscope analysis of the catalysts: (a) Cu/Ti (50 000:1); (b) Ce/Ti (50 000:1); (c) CuCe/Ti (50 000:1); (d) Cu/Ti (20 000:1); (e) Ce/Ti (20 000:1); and (f) CuCe/Ti (20 000:1).
too high voltage, part of HgO (as shown in eqs 5 and 6) adsorbed on the inner wall of the quartz tube would be reduced to elemental mercury under the influence of discharge arc, thus reducing the $\eta_{\text{Hg}}$.

\[ e + O_2 \rightarrow O + O^* \]  
\[ e + N_2 \rightarrow N + N^* \]  
\[ N^* + O_2 \rightarrow \text{NO + O}^* \]  
\[ \text{O}^* + O_2 \rightarrow O_3 \]  
\[ \text{Hg}_0^* + \text{O}^* \rightarrow \text{HgO} \]  
\[ \text{Hg}_0 + O_3 \rightarrow \text{HgO} + O_2 \]  

3.3. Effects of NO, SO$_2$, and H$_2$O(g) on $\eta_{\text{Hg}}$. The composition of flue gas is very complex, including O$_2$, CO$_2$, N$_2$, SO$_2$, NO$_x$, H$_2$O, and HCl. When DBD is used to treat flue gas, multiple components can react with high-energy electrons to generate different active substances and free radicals and undergo redox reactions with O$_3$ and *O, thereby affecting the conversion of Hg$^0$. In this section, we used the controlled variable method to study the influences of NO, SO$_2$, and H$_2$O(g) on the $\eta_{\text{Hg}}$.

NO will be oxidized by active materials and affect the $\eta_{\text{Hg}}$. An et al.$^{44}$ found that the presence of NO will reduce the $\eta_{\text{Hg}}$ because the reaction rate constant of the reaction of NO and O$_3$ was much greater than that of NO and Hg$^0$, so NO would compete with Hg$^0$ for active substances. However, some others$^{27,34}$ believed that NO provides additional O atoms to increase the active materials and promote the oxidation of Hg$^0$. The NO concentration dependence of $\eta_{\text{Hg}}$ was shown in Figure 7 (O$_2$ concentration was 6%).

\[ \text{NO} + \text{O}^* \rightarrow \text{NO}_2 \]  
\[ \text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2 \]  
\[ \text{NO}_2 + \text{O}_3 \rightarrow \text{NO}_3 + \text{O}_2 \]

The effect of SO$_2$ concentration on $\eta_{\text{Hg}}$ is shown in Figure 8 (O$_2$ concentration was 6%).

Different from Figure 6, the $\eta_{\text{Hg}}$ quickly reached about 95% in the range of 3–8 kV, and the concentration of SO$_2$ at the outlet also decreased continuously with the increase in voltage. Wang et al.$^{48}$ found that SO$_2$ consumes O atoms and inhibits the conversion of Hg$^0$. However, some researchers$^{20,24,33}$ believed that SO$_2$ is mainly oxidized by *OH and *O to HSO$_3^-$ and SO$_3$, which had little effect on the conversion of Hg$^0$. Through our experimental data, we found that the generated HSO$_3^-$ and SO$_3$ react with HgO to generate HgSO$_4$, thereby oxidizing part of Hg$^0$. The main reactions include eqs 10–13; however, there is still controversy about how SO$_2$ affects the oxidation of Hg$^0$.

\[ \text{SO}_2 + \text{O}^* \rightarrow \text{SO}_3 \]  
\[ \text{HgO} + \text{SO}_3 \rightarrow \text{HgSO}_4 \]  
\[ \text{Hg}_0^* + \text{O}^* \rightarrow \text{HgO} \]
To clarify the effect of H₂O(g) content on the η₄Hg, we generated a certain amount of water vapor by bubbling and heating, and introduced the water vapor into the DBD reactor through N₂, and obtained the corresponding absolute humidity based on the flow rate. The result is shown in Figure 9 (O₂ concentration was 6%).

When there was no H₂O in the reactor, the η₄Hg reached a peak of 93.5% at 9.5 kV. When there was H₂O, the η₄Hg decreased with the increase in H₂O(g). The chemical process in the DBD reactor is shown in eqs 14−17, indicating that water vapor can consume part of O₃, thereby inhibiting the oxidation of Hg⁰.

Hg⁰ + O₃ → HgO + O₂ 
H₂O + O₂ → H₂O₂ + O₂ 
H₂O₂ → OH⁻ + OH⁻ 
Hg⁰ + OH⁻ → Hg(OH)₂ 
Hg⁰ + O₃ → HgO + O₂ 

The effect of the coexistence of NO and SO₂ on the η₄Hg was shown in Figure 10. Under 6% O₂ concentration, the η₄Hg was the highest when only SO₂ was present, which can reach 95.6% at 4 kV and 100% at 9 kV. The η₄Hg was the lowest when only NO was present, which indicated again that SO₂ promotes the oxidation of Hg⁰, while NO inhibits the oxidation of Hg⁰. When the inlet gas was composed of 70 μg/m³ Hg⁰ + 6% O₂ + 300 mg/m³ NO + 1000 mg/m³ SO₂, a η₄Hg of 93% was achieved at 9.5 kV. However, adding H₂O(g) to this inlet gas would reduce the η₄Hg. For example, when the 2% H₂O was introduced in the above inlet gas, the η₄Hg rapidly dropped from 93 to 86.3%; when the introduced H₂O content was 5%, the η₄Hg dropped to 79.9%. Therefore, it is best to conduct dehydration first when using DBD-CuCe/Ti reactor to oxidize Hg⁰ or simultaneously oxidize multiple pollutants in the flue gas. Besides, the flue gas HCl affects the redox reaction, although the chemical properties of the flue gas CO₂ are very stable, the concentration of CO₂ is relatively high. Hence, it is necessary to investigate the influence of HCl and CO₂ on the oxidation of multipollutants in future work.

4. CONCLUSIONS

To efficiently oxidize Hg⁰ in the flue gas, we prepared the CuCe/Ti catalyst and proposed a new method of DBD coupling the CuCe/Ti catalytic oxidation. The experiment showed that DBD coupling CuCe/Ti reactor to oxidize Hg⁰ or simultaneously oxidize multiple pollutants in the flue gas is promising.

(1) the oxides of Cu–Ce had higher catalytic activity than the single metal oxides;
(2) when the discharge voltage was about 9.5 kV, the maximum η₄Hg reached 93%, which means both the energy density and η₄Hg were satisfactory;
(3) the oxidation of Hg⁰ was mainly due to the oxidation from O₂, *OH, and O₃, but the intermediate products also affected the η₄Hg; and
(4) O₂ and SO₂ were favorable for the oxidation of Hg⁰, but increasing NO and H₂O tended to decrease η₄Hg.

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Notes

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References

(1) Kershaw, T. G.; Clarkson, T. W.; Dhahir, P. H. The Relationship Between Blood Levels and Dose of MeHg in Man. Arch. Environ. Health. 1980, 35, 28–36.
(2) Pacyna, E. G.; Pacyna, J. M.; Sundseth, K.; Munthe, J.; Kindbom, K.; Wilson, S.; Steenhuisen, F.; Maxson, P. Global emission of mercury to the atmosphere from anthropogenic sources in 2005 and projections to 2020. Atmos. Environ. 2010, 44, 2487–2499.
(3) Feng, X.; Streets, D.; Hao, J.; Wu, Y.; Li, G. Mercury Emissions from Industrial Sources in China. In Mercury Fate and Transport in the Global Atmosphere; Springer: Boston, MA, 2009; pp 67–79.
(4) Akers, D.; Raleigh, C. The Mechanisms of Trace Element Removal During Coal Cleaning. Coal Prep. 1998, 19, 257–269.
(5) Wu, Q.; Wang, S.; Li, G.; Liang, S.; Lin, C.; Wang, Y.; Cai, S.; Liu, K.; Hao, J. Temporal Trend and Spatial Distribution of Speciated Atmospheric Mercury Emissions in China During 1978-2014. Environ. Sci. Technol. 2016, 50, 13428–13435.
(6) Luo, G.; Yao, H.; Xu, M.; Gupta, R.; Xu, Z. Identifying modes of occurrence of mercury in coal by temperature programmed pyrolysis. Proc. Combust. Inst. 2011, 33, 2763–2769.
(7) Wdowin, M.; Wiatrowska-Motyk, M. M.; Panek, R.; Stevens, L. A.; Franus, W.; Snape, C. E. Experimental study of mercury removal from exhaust gases. Fuel 2014, 128, 451–457.
(8) Wang, B.; Xu, X.; Xu, W.; Wang, N.; Xiao, H.; Sun, Y.; Huang, H.; Yu, L.; Fu, M.; Wu, J.; et al. The Mechanism of Non-thermal Plasma Catalysis on Volatile Organic Compounds Removal. Catal. Surv. Asia 2018, 22, 73–94.
(9) Subrahmanyam, C.; Magureanu, M.; Renken, A.; Kiwi-Minsker, L. Catalytic abatement of volatile organic compounds assisted by non-thermal plasma: Part I. A novel dielectric barrier discharge reactor containing catalytic electrode. Appl. Catal., B 2006, 65, 150–156.
(10) Guo, Q.; With, P.; Liu, Y.; Gläser, R.; Liu, C. Carbon template removal by dielectric-barrier discharge plasma for the preparation of zirconia. Catal. Today 2013, 211, 156–161.
(11) Wang, J.; Wang, W.; Xu, W.; Wang, X.; Zhao, S. Mercury removals by existing pollutants control devices of four coal-fired power plants in China. J. Environ. Sci. 2011, 23, 1839–1844.
(12) Liu, L.; Zheng, C.; Wu, S.; Gao, X.; Ni, M.; Cen, K. Manganese-cerium oxide catalysts prepared by non-thermal plasma for NO oxidation: Effect of O2 in discharge atmosphere. Appl. Surf. Sci. 2017, 416, 78–85.
(13) Niu, Q.; Luo, J.; Xia, Y.; Sun, S.; Chen, Q. Surface modification of bio-char by dielectric barrier discharge plasma for Hg removal. Fuel Process. Technol. 2017, 156, 310–316.
(14) Liu, Y.; Wang, Y.; Wang, H.; Wu, Z. Catalytic oxidation of gas-phase mercury over Co/TiO2 catalysts prepared by sol–gel method. Catal. Commun. 2011, 12, 1291–1294.
(15) Byun, Y.; Koh, D. J.; Shin, D. N. Removal mechanism of elemental mercury by using non-thermal plasma. Chemosphere 2011, 83, 69–75.
(16) Ma, H.; Chen, P.; Zhang, M.; Lin, X.; Ruan, R. Study of SO2 Removal Using Non-thermal Plasma Induced by Dielectric Barrier Discharge (DBD). Plasma Chem. Plasma Process. 2002, 22, 239–254.
(17) Wang, T.; Liu, H.-Z.; Yang, B.; Sun, B.-M.; Xiao, H.-P.; Zhang, Y. Effect of plasma-catalyst system on NO removal using M–Cu (M = Mn, Ce, Co, and Fe) catalysts. Jpn. J. Appl. Phys. 2016, 55, No. 116202.
(18) Shen, Y.; Zong, Y.; Ma, Y.; Zhu, S.; Jin, Q. Synergistic catalytic removals of NOx and CO and C6H6 over CeSn0.75W0.25O5/TiAl2O5. Fuel 2016, 180, 727–736.
(19) Piumetti, M.; Fino, D.; Russo, N. Mesoporous manganese oxides prepared by solution combustion synthesis as catalysts for the total oxidation of VOCs. Appl. Catal., B 2015, 163, 277–287.
(20) Zhang, X.; Wang, J.; Tan, B.; Zhang, N.; Bao, J.; He, G. Ce-Co interaction effects on the catalytic performance of uniform mesoporous Ce0.6Co0.4 catalysts in Hg2+ oxidation process. Fuel 2018, 226, 18–26.
(21) Tian, W.; Yang, H.; Fan, X.; Zhang, X. Catalytic reduction of NOx with NH3 over different-shaped MnO2 at low temperature. J. Hazard. Mater. 2011, 188, 105–109.
(22) Li, L.; Shen, Q.; Cheng, J.; Hao, Z. Catalytic oxidation of NO over TiO2 supported platinum clusters I. Preparation, characterization and catalytic properties. Appl. Catal., B 2010, 93, 259–266.
(23) Li, P.; Chen, X.; Li, Y.; Schwank, J. W. Effect of preparation methods on the catalytic activity of La0.8Sr0.2CoO3 perovskite for CO and C6H6 oxidation. Catal. Today 2020, DOI: 10.1016/j.cattod.2020.03.012.
(24) An, J.; Lou, J.; Meng, Q.; Zhang, Z.; Ma, X.; Li, J. Non-thermal plasma injection-CeO2-WO3/TiO2 catalytic method for high-efficiency oxidation of elemental mercury in coal-fired flue gas. Chem. Eng. J. 2017, 325, 708–714.
(25) Ouyang, B.; Zhang, Y.; Zhang, Z.; Fan, H. J.; Rawat, R. S. Nitrogen-Plasma-Activated Hierarchical Nickel Nitride Nanocorals for Energy Applications. Small 2017, 13, No. 1604265.
(26) Zhang, Y.; Ouyang, B.; Xu, J.; Jia, G.; Chen, S.; Rawat, R. S.; Fan, H. J. Rapid Synthesis of Cobalt Nitride Nanowires: Highly Efficient and Low-Cost Catalysts for Oxygen Evolution. Angew. Chem., Int. Ed. 2016, 55, 8670–8674.
(27) Huang, C.; Bai, S.; Lv, J.; Li, Z. Characterization of Silica-Supported Cobalt Catalysts Prepared by Decomposition of Nitrates Using Dielectric-Barrier Discharge Plasma. Catal. Lett. 2011, 141, 1391–1398.
(28) Sousa, J. P. S.; Pereira, M. F. R.; Figueiredo, J. L. Catalytic oxidation of NO to NO2 on N-doped activated carbons. Catal. Today 2011, 176, 383–387.
(29) Cui, S.; Hao, R.; Fu, D. An integrated system of dielectric barrier discharge combined with wet electrostatic precipitator for simultaneous removal of NO and SO2: Key factors assessments, products analysis and mechanism. Fuel 2018, 221, 12–20.
(30) Cui, S.; Hao, R.; Fu, D. Integrated method of non-thermal plasma combined with catalytic oxidation for simultaneous removal of SO2 and NO. Fuel 2019, 246, 365–374.
(31) Cui, S.; Zhong, Z.; Liao, Y.; Qi, L.; Fu, D. Simultaneous Removal of NO and SO\textsubscript{2} via an Integrated System of Nonthermal Plasma Combined with Catalytic Oxidation and Wet Electrostatic Precipitator. Energy Fuels 2019, 33, 10078–10089.

(32) Zhang, J.; Duan, Y.; Zhao, W.; Zhu, C.; Zhou, Q.; Ding, W. Study on Elemental Mercury Oxidation by Non-thermal Plasma with Calcium Chloride Enhancement. Plasma Chem. Plasma Process. 2018, 38, 573–586.

(33) Zhang, J.; Duan, Y.; Zhao, W.; Zhu, C.; Zhou, Q.; She, M. Removal of Elemental Mercury from Simulated Flue Gas by Combining Non-thermal Plasma with Calcium Oxide. Plasma Chem. Plasma Process. 2016, 36, 471–485.

(34) Gao, X.; Liu, S.; Zhang, Y.; Luo, Z.; Cen, K. Physicochemical properties of metal-doped activated carbons and relationship with their performance in the removal of SO\textsubscript{2} and NO. J. Hazard. Mater. 2011, 188, 58–66.

(35) Zhong, L.; Cai, W.; Yu, Y.; Zhong, Q. Insights into synergistic effect of chromium oxides and ceria supported on Ti-PILC for NO oxidation and their surface species study. Appl. Surf. Sci. 2015, 325, 52–63.

(36) Li, X.; Zhang, S.; Jia, Y.; Liu, X.; Zhong, Q. Selective catalytic oxidation of NO with O\textsubscript{3} over Ce-doped MnO\textsubscript{x}/TiO\textsubscript{2} catalysts. J. Nat. Gas Chem. 2012, 21, 17–24.

(37) Wang, M.; Liu, H.; Huang, Z.-H.; Kang, F. Activated carbon fibers loaded with MnO\textsubscript{2} for removing NO at room temperature. Chem. Eng. J. 2014, 256, 101–106.

(38) Liu, L.; Yao, Z.; Liu, B.; Dong, L. Correlation of structural characteristics with catalytic performance of CuO/ZeO\textsubscript{x} catalysts for NO reduction by CO. J. Catal. 2010, 275, 45–60.

(39) Pang, L.; Fan, C.; Shao, L.; Song, K.; Yi, J.; Cai, X.; Wang, J.; Kang, M.; Li, T. The Ce doping Cu/ZSM-5 as a new superior catalyst to remove NO from diesel engine exhaust. Chem. Eng. J. 2014, 253, 394–401.

(40) Xiong, Y.; Tang, C.; Yao, X.; Zhang, L.; Li, L.; Wang, X.; Deng, Y.; Gao, F.; Dong, L. Effect of metal ions doping (M=Ti\textsuperscript{4+}, Sn\textsuperscript{4+}) on the catalytic performance of MnO\textsubscript{x}/CeO\textsubscript{2} catalyst for low temperature selective catalytic reduction of NO with NH\textsubscript{3}. Appl. Catal., A 2015, 495, 206–216.

(41) Liu, L.; Gao, X.; Song, H.; Zheng, C. H.; Zhu, X.-B.; Luo, Z.-Y.; Ni, M.-J.; Chen, K.-F. Study of the promotion effect of Iron on supported manganese catalysts for NO Oxidation. Aerosol Air Qual. Res. 2014, 14, 1038–1046.

(42) Cai, W.; Zhao, Y.; Chen, M.; Jiang, X.; Wang, H.; Ou, M.; Wan, S.; Zhong, Q. The formation of 3D spherical Cr-Ce mixed oxides with roughness surface and their enhanced low-temperature NO oxidation. Chem. Eng. J. 2018, 333, 414–422.

(43) Yang, Z.; Li, H.; Liu, X.; Li, P.; Yang, J.; Lee, P.-H.; Shih, K. Promotional effect of CuO loading on the catalytic activity and SO\textsubscript{2} resistance of MnO\textsubscript{x}/TiO\textsubscript{2} catalyst for simultaneous NO reduction and Hg\textsuperscript{2+} oxidation. Fuel 2018, 227, 79–88.

(44) An, J.; Shang, K.; Lu, N.; Jiang, Y.; Wang, T.; Li, J.; Wu, J. Oxidation of Elemental Mercury by Active Species Generated From a Surface Dielectric Barrier Discharge Plasma Reactor. Plasma Chem. Plasma Process. 2014, 34, 217–228.

(45) Liu, K.; Zheng, Z.; Liu, S.; Hu, Y. Study on the Physical and Chemical Characteristics of DBD: The Effect of N\textsubscript{2}/O\textsubscript{2} Mixture Ratio on the Product Regulation. Plasma Chem. Plasma Process. 2019, 39, 1255–1274.

(46) Majumdar, A.; Singh, R. K.; Palm, G. J.; Hippler, R. Dielectric barrier discharge plasma treatment on E. coli: Influence of CH\textsubscript{4}/N\textsubscript{2}, O\textsubscript{2}/N\textsubscript{2}, O\textsubscript{3}/N\textsubscript{2} and Ar gases. J. Appl. Phys. 2009, 106, No. 084701.

(47) Zhang, Y.; Tang, X.; Yi, H.; Yu, Q.; Wang, J.; Gao, F.; Gao, Y.; Li, D.; Gao, Y. The byproduct generation analysis of the NO\textsubscript{3} conversion process in dielectric barrier discharge plasma. RSC Adv. 2016, 6, 63946–63953.

(48) Wang, Z. H.; Jiang, S. D.; Zhu, Y. Q.; Zhou, J. S.; Zhou, J. H.; Li, Z. S.; Cen, K. F. Investigation on elemental mercury oxidation mechanism by non-thermal plasma treatment. Fuel Process. Technol. 2010, 91, 1395–1400.

(49) Luo, J.; Niu, Q.; Xia, Y.; Cao, Y.; Du, R.; Sun, S.; Lu, C. Investigation of Gaseous Elemental Mercury Oxidation by Non-thermal Plasma Injection Method. Energy Fuels 2017, 31, 11013–11018.

(50) Zhang, Y.; Zhang, Y.; Wang, T.; Lin, J.; Romero, C. E.; Pan, W. Oxidation of elemental mercury with non-thermal plasma coupled with a wet process. Fuel 2017, 197, 320–325.