MERCURY EMISSIONS IN A 50kW$_{th}$ OXY-FUEL CIRCULATING FLUIDIZED BED WITH RECYCLED WARM FLUE GAS

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ABSTRACT: This study evaluates mercury speciation and the effects of HCl, NO, steam and SO_2 on mercury emission and its speciation from the combustion of Chinese bituminous coal and American bituminous coal under O_2/CO_2 atmosphere especially with recycled warm flue gas in a 50 kW$_{th}$ circulating fluidized bed. Compared to air coal combustion, higher gaseous mercury concentration and higher percentage of Hg^{2+} under oxy-coal combustion were observed. Moreover, HCl, NO, SO_2 and steam could cause the percentage of Hg^{2+} to increase. Compared to the air atmosphere, larger steam concentration under the oxy atmosphere played a significant role in promoting mercury oxidation. HCl promoted mercury oxidation via O and Cl radicals under oxy-combustion. These results are very significant for alternative methods of Hg removal under oxy-fuel combustion.

1. INTRODUCTION

China is going to decrease greenhouse gas emissions per unit of GDP in 2020 by 40% to 45% from its 2005 level (Yu et al. 2013). Meanwhile, CO_2 is becoming a restricted discharge pollutant in the U.S. and Europe (Moorman et al. 2011). Many new technologies such as chemical-looping combustion, oxy-fuel combustion, and others are being developed to capture CO_2.

Oxy-fuel combustion is recognized as one of the most advanced technologies (Buhre et al. 2005, Duan et al. 2009). Some aspects of oxy-fuel combustion technology are not well understood, such as its operational parameters and its coal combustion characteristics (Buhre et al. 2005, Jia et al. 2012). The flue gas characteristics under oxy-combustion are different from those under air combustion such as higher SO_2 concentration, lower NO_X concentration (Lupiáñez et al. 2013) and different steam concentration(Hecht et al. 2012). Of course, the different recycled flue gas extracted location have different types of flue gas recirculation. Oxy-fuel combustion has two main types of flue gas recirculation: cold-recycle and warm-recycle. Under cold-recycle flue gas condition, the recycled flue gas is extracted after the wet flue gas desulfurization scrubber, and the recycled flue gas contains only tiny amount of moisture (Hu et al. 2011). Under warm-recycle flue gas condition, the recycled flue gas is taken before the bag filter and after the air heater, so water is not removed in the recycled flue gas (McCauley et al. 2009, Hu et al. 2011). There are few reports (Duan et al. 2014) regarding oxy-fuel circulating fluidized beds with recycled warm flue gas. During recycled warm flue gas(Duan et al. 2014), there are some difference from other types of recycle due to the higher moisture and SO_2 concentration in the recycle loop.

Mercury and its compounds are harmful to both the environment and the health of human beings (Omine et al. 2012). Mercury also jeopardizes the CO_2 storage system for oxy-fuel combustion (Roy et al. 2014). Elemental mercury can corrode the CO_2 processing units, such as brazed aluminum heat exchangers through an amalgamation process (Santos 2010). To enhance the safety of CO_2 capture and storage system in oxy-fuel circulating fluidized beds, mercury should be removed to levels below detectable limits (Mitsui et al. 2011, Font et al. 2012). Moreover, mercury form is very important for mercury removal.

There are three speciations of mercury in flue gas (Senior et al. 2000): elemental mercury (Hg^0), oxidized mercury (Hg^{2+}) and particulate mercury (Hg_p). Oxidized mercury and particulate-bound mercury are easy to control. Elemental mercury is difficult to remove due to its insolubility in water (Yang et al. 2007) and high volatility. It is essential to pay attention to mercury speciation under oxy-coal combustion (Yokoyama et al. 2000).

There are few studies concerning mercury speciation during oxy-coal combustion. Achariya Suriyawong (Suriyawong et al. 2006, Suriyawong et al. 2008) reported that there are no differences in mercury speciation under air or O_2/CO_2 atmosphere. Some other authors (Yokoyama et al. 2000, Gharebaghi 2009, Font et al. 2012, Wu et al. 2013) obtained data about mercury oxidation under oxy-fuel combustion. Other researchers (Gharebaghi et al. 2011, Contreras et al. 2013) investigated mercury behavior under oxy-fuel combustion by simulation or equilibrium calculations. M. Gharebaghi (Gharebaghi et al. 2011) tried to predict mercury oxidation under oxy-fuel conditions through a combined homogeneous-heterogeneous model. M.L. Contreras (Contreras et al. 2013) used thermodynamical equilibrium calculation to evaluate the fate of trace metals under oxy coal combustion with biomass and coal/biomass blends. However, little research about the fate of mercury under an oxy-fuel circulating fluidized bed combustor with recycled warm flue gas existing.

This paper reports experimental results exploring mercury speciation under air and oxy-coal combustion atmospheres. These experiments were conducted in a 50 kW_{th} oxy-fuel circulating fluidized bed combustor with recycled warm flue gas using Chinese bituminous coal and American bituminous coal. The effect of HCl, NO, steam and SO_2 on mercury emission and its speciation were also studied. All of the results reported under oxy-coal combustion were compared to those under air-coal combustion. To the industry, the results about emissions of CO, CO_2, NO and temperature distribution are helpful for optimizing parameters of power plants and the results about mercury speciation are useful for mercury controlling under oxy-coal combustion.

2. EXPERIMENTAL SECTION.

2.1. Feedstock. Chinese bituminous coal and American bituminous coal were chosen as the solid fuel with 0-6 mm particle sizes. Ultimate and proximate analyses of the coal are summarized in Table 1. The Ca-based sorbents used were limestone with 0-1 mm particle sizes. Table 2 shows the composition of the limestone.

Table 1. Ultimate and proximate analyses of Chinese coal and American coal.

Coal	Ultimate analysis (%)					Lower Heating	Proximate analysis (wt. %)				Hg
	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}	$MJ \cdot Kg^{-1}$	FC_{ar}	V_{ar}	A_{ar}	M_{ar}	$\mu g \cdot kg^{-1}$
CN	64.09	3.80	9.81	0.75	0.49	25.05	51.68	28.38	16.18	3.76	56.89
US	62.14	4.26	8.63	0.96	2.93	26.66	49.68	35.34	9.85	5.13	40.13

CN: Chinese bituminous coal;US: American bituminous coal; chinFC_{ar}: Fixed carbon; V_{ar}: Volatile matter; A_{ar}: Ash; M_{ar}: Moisture.

The Ca/S molar ratio that was 2.5 under air combustion while Ca/S molar ratio was 4.0 under oxy-combustion with both Chinese bituminous coal and American bituminous coal. The reason the Ca/S molar ratio was increased from 2.5 to 4.0 was a limitation of our measurement conditions. If the Ca/S molar ratio was 2.5 under oxy-combustion, as it was under air combustion, the SO_2 concentration would exceed the acceptable range.

Table 2. Limestone analysis.

Composition	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	SO_3
Content (wt. %)	55.990	0.538	0.392	0.100	0.050	0.041	0.038
Composition	Cl	SrO	K_2O	P_2O_5	TiO_2	LOI*	_
Content (wt. %)	0.022	0.017	0.015	0.010	0.004	42.770	_

*LOI: Loss of incineration.

2.2. Experimental Installation. The experiments were conducted in a 50 kW_{th} oxy-coal circulating fluidized bed combustor with recycled warm flue gas. The fluidized bed system was set up to study mercury speciation in oxy-coal combustion, as shown in Fig. 1. The height of the circulating fluidized bed body is 5200 mm with three sections. The dense zone is 1000 mm in height and 122 mm in inner diameter, the recycling zone is 200 mm, and the dilute zone is 4000 mm in height and 150 mm in inner diameter. The experimental system contained the coal feeding system, the gas mixing system, the fluidized bed body, the temperature control system, the exhaust cleaning system, and the warm recycle system. The temperature of the recycle flue gas was controlled to remain over 180°C to avoid condensation of the vapor in the recycle loop (Duan et al. 2014). Flue gas was sampled from the location between the outlet of furnace and the inlet of bag filter.

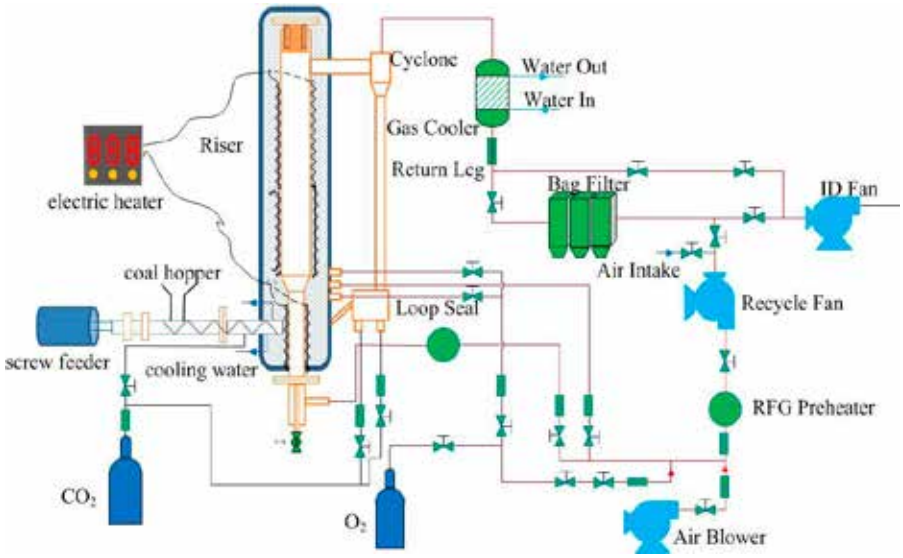

Fig. 1. Schematic diagram of mercury oxidation during warm recycle oxy-coal atmosphere in circulating fluidized bed.

2.3. Determination of NO, SO_2 and H_2O. O_2, SO_2, NO, NO_2, CO and CO_2 were recorded on a dry basis by the J2KN online analyzer. The detection range and error for J2KN online analyzers are listed here: O_2 (Range: 0-21%; Accuracy: ±0.2%), CO (0-10000 ppm; ±20 ppm), NO (0-5000 ppm; ±5 ppm), NO_2 (0-1000 ppm; ±5 ppm), SO_2 (0-5000 ppm; ±10 ppm), CO_2 (0-100%; ±0.2% measured). The MAC125 moisture sensor detected H_2O.

2.4. Determination of HCl. The HJ 548-2009 method recommended by the Ministry of Environmental Protection of China was used to determine hydrogen chloride concentration in flue gas.

2.5. Determination of Hg. The Ontario Hydro Method (OHM) recommend by the American Environmental Protection Agency was used to determine elemental mercury, oxidized mercury, particulate mercury and total gaseous mercury. The concentrations of Hg in coal, slag, and fly ash were obtained from DMA80. The data for gaseous mercury was obtained from Hydra AA analyzer.

The mercury mass balance is based on the total input of mercury and the total output of mercury. The total input of mercury is the total amount of mercury in the coal; the total output of mercury is the sum of the mercury in the flue gas, fly ash and bottom ash. If this mass balance is within the range of 70%-130% (Lee et al. 2006), all of these data based on the experiments with the Ontario Hydro method and EPA Method 26A would be accurate.

2.6 Experimental system Our previous research (Duan et al. 2014) has listed the detailed operational parameters of the test. Here we list some relevant major operational parameters. The primary oxidant faction was 0.7 in both air coal combustion and oxy coal combustion. In addition, the thermal input was kept constant. The coal-feeding rate was kept 5-8 kg/h in all tests.

3. RESULTS AND DISCUSSION

The closures determined for total mercury mass balances were in the range of 80.03% to 105.60%, suggesting good accuracy in the tests (Yokoyama et al. 2000), as is shown in Fig. 2.

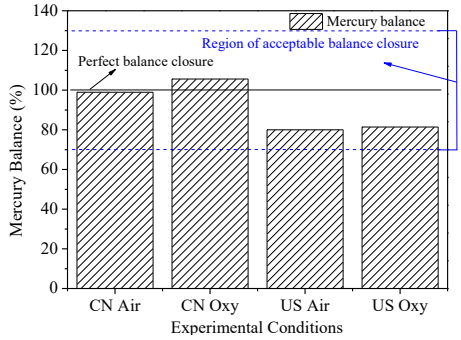

Fig. 2. Mercury mass balance.

3.1. Mercury concentration under air and oxy-combustion. Mercury concentration using Chinese bituminous coal and American bituminous coal under air and oxy-combustion were compared in Fig. 3. It can be observed that the concentration of Hg^{2+} was higher under oxy-combustion than that under air combustion with both Chinese bituminous coal and American bituminous coal. The accumulation of unburnt carbon in the furnace during recycled warm flue gas can reduce the concentration of total mercury in the flue gas. These conclusions were consistent with the observations by Yoshiaki Mitsui (Mitsui et al. 2011), who found total Hg concentration was greater under oxy-combustion than that under air combustion through a 1.5 MWth combustion test facility. This phenomenon can be linked to the higher overall oxygen content of oxy-combustion compared with that of air combustion.

3.2. Mercury speciation under air and oxy-combustion. From Fig. 4, it can be observed that the percentage of Hg^{2+} was higher under oxy-combustion than that under air combustion. Similar results were reported by Achariya Suriyawong (Suriyawong et al. 2013). Moreover, the percentage of Hg^0 and Hg^{2+} was lower with American bituminous coal under both air and oxy-combustion than that with Chinese bituminous coal. The higher mercury oxidized ratio verified that the oxy-combustion system had better performance in this research. The effects of different coals on mercury emission and its speciation can be correlated with the different contents of S and Cl in the coal.

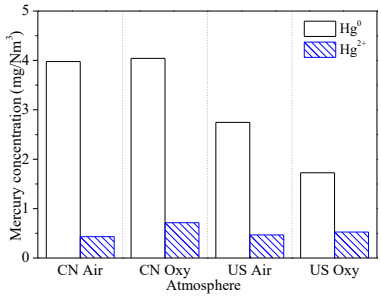

Fig. 3. Mercury concentration under air and O_2/CO_2 atmosphere with different coals.

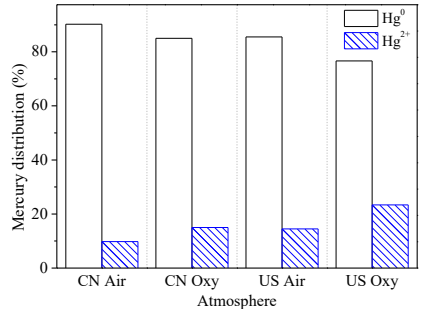

Fig. 4. Mercury emission and its speciation under air and O_2/CO_2 atmosphere with different coals.

Fig. 4 shows approximately 85% elemental mercury and 15% oxidized mercury under air combustion using Chinese bituminous coal. It also shows approximately 76.62% elemental mercury and 23.38% oxidized mercury under oxy-combustion using Chinese bituminous coal. The results indicated that it was important to select the right method to remove Hg for avoiding mercury corrosion of the CO_2 storage system through an amalgamation process (Wall et al. 2011, Wall et al. 2013).

3.3. Effect of unburnt carbon on particulate mercury concentration under air and oxy-combustion. Unburnt carbon in fly ash was one of the key factors in affecting the concentration of particulate mercury in flue gas (Senior et al. 2005). As is shown in Fig. 5, the results indicate that the particulate mercury concentration decreases when the unburnt carbon concentration increase, and the particulate mercury concentration is higher in oxy-combustion than that of air combustion. Senior (Senior et al. 2005) also obtained

that similar results: higher carbon in the ash can intensify mercury removal ratio. This result was attributed to the accumulation of particulate mercury in the furnace resulting from recycled warm flue gas. Moreover, the unburnt carbon can reduce the particulate mercury in flue gas, resulting in the decrease of the concentration of total gaseous mercury.

3.4. Effect of HCl emission on mercury oxidation under air and oxy-combustion. The chlorine in coal existed mainly in form of HCl after combustion. HCl concentration had an important influence on the fate of mercury (Senior et al. 2000). Therefore, it was necessary to understand the effect of HCl emission on mercury oxidation under oxy-combustion compared with that under air combustion. The results from Fig. 6 show the percentage of Hg^{2+} increases with HCl concentration increases, which was common to several other studies

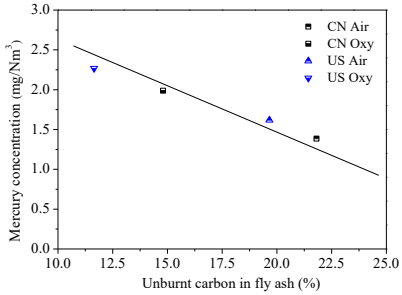

Fig. 5. Effect of unburnt carbon on particulate mercury under air and O_2/CO_2 atmosphere with different coals.

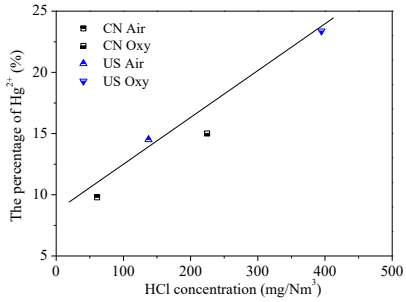

Fig. 6. Effect of HCl emission on mercury concentration under air and O_2/CO_2 atmosphere with different coals.

(Galbreath et al. 2000, Laudal et al. 2000). It can be inferred that Eq. (1) (Roesler et al. 1995) became the dominated mechanism for the generation of the OH radical and the Cl radical due to the enriched oxygen concentration under oxy-combustion. Then, the Cl radical subsequently oxidized Hg^0 and HgCl was transformed into $HgCl_2$ via the mechanism shown in Eq. (2) (Widmer et al. 2000) and Eq. (3) (Widmer et al. 2000).

$$HCl + O \rightarrow OH + Cl \quad (1)$$

$$Hg + Cl + M \rightarrow HgCl + M \quad (2)$$

$$HgCl + Cl + M \rightarrow HgCl_2 + M \quad (3)$$

3.5. Effect of NO emission on mercury oxidation under air and oxy-combustion. NO concentration had a complex influence on mercury oxidation. Therefore, it was essential to explore how NO concentration affected mercury oxidation under oxy-combustion. From Fig. 7, it can be noted that NO increases the percentage of Hg^{2+} under both air and oxy-combustion. The results from some reports (Wang et al. 2009) that measured NO concentration and mercury speciation in the fuel gas from five coal-fired power stations in China were consistent with this study. Some reports (Wu et al. 2013) were not in agreement with this finding, indicating the effect of NO on mercury oxidation depends on the NO concentration.

3.6. Effect of steam on mercury oxidation under air and oxy-combustion. Under oxy-combustion with recycled warm flue gas, steam had a significant effect on mercury oxidation (Niksa et al. 2001, Fernández-Miranda et al. 2014), especially compared to that under air combustion. As shown in Fig. 8, the percentage of steam is much higher (between 17.4% and 21.1%) under oxy-combustion than that under air combustion (between 7.1% and 7.4%). The higher percentage of H_2O promotes mercury oxidation. These findings were also in line with the observations of other researchers (Fernández-Miranda et al. 2014). Nuria Fernández-Miranda (Fernández-Miranda et al. 2014) reported that mercury oxidation was preferred by water vapor in all cases.

Due to the enriched oxygen concentration and higher water vapor concentration under oxy-combustion, Eq. (4) (Yang et al. 2007) became the biggest source of the OH radical. Enriched steam and oxygen caused an enrichment of the OH radical. The OH radical is an important factor in increasing the percentage of Hg^{2+}. This may be the reason for higher steam concentration increasing the percentage of Hg^{2+}.

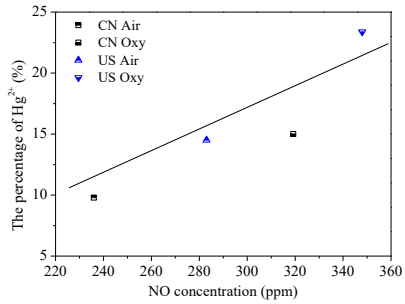

Fig. 7. Effect of NO emission on mercury oxidation under air and O_2/CO_2 atmosphere with different coals.

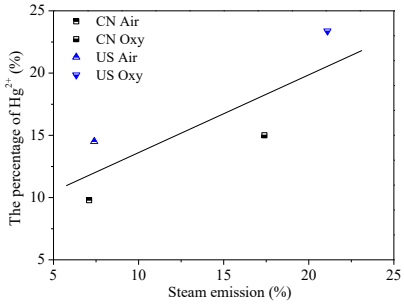

Fig. 8. Effect of steam emission on mercury oxidation under air and O_2/CO_2 atmosphere with different coals.

$$H_2O + O \rightarrow OH + OH \quad (4)$$

3.7. Effect of SO_2 emission on mercury oxidation under air and oxy-combustion. SO_2 concentration was significantly greater under oxy-combustion than that under air combustion. Along with the higher percentage of steam, a higher percentage of SO_3 also formed. It was worth exploring how the higher SO_2 and SO_3 percentage would influence mercury oxidation under oxy-combustion. The effect of SO_2 emission on mercury oxidation under air and oxy-combustion is shown in Fig. 9. The results show that mercury oxidation is promoted when the SO_2 concentration increase. This was consistent with the observations of Reinhold Spörla (Spörl et al. 2014). However, our results were different from the results of Brydger Van Otten (Van Otten et al. 2011), who concluded that there was an increase in mercury oxidation only if SO_2 concentration was higher than 400 ppmv. Li (Li et al. 2013) found that under different flue gas conditions, the effect of SO_2 on mercury oxidation was also different, even on the contrary. Other people (Agarwal et al. 2006, Zhuang et al. 2007) also found the complex relationship between Hg^0 and SO_2.

According to Eq. (5) (Wu et al. 2013), mercury can be oxidized by SO_2 in the presence of oxygen. This indicated that SO_2 can promote mercury oxidation in the presence of O_2. This was the reason that mercury oxidation was promoted by increasing the SO_2 concentration.

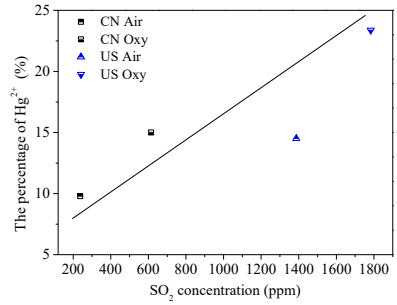

Fig. 9. Effect of SO_2 emission on mercury oxidation under air and O_2/CO_2 atmosphere with different coals.

$$Hg + SO_2 + O_2 \rightarrow HgSO_4 \quad (5)$$

4. CONCLUSION

The effect of HCl, NO, H_2O and SO_2 on mercury speciation under circulating fluidized bed oxy-firing with recycled warm flue gas have been investigated. A series of experimental tests have been conducted in a 50 kW_{th} combustor for Chinese bituminous coal and American bituminous coal. The results are compared with conventional air combustion. The gaseous mercury concentration was higher under oxy-coal combustion than that under air-coal combustion. Moreover, the oxy atmosphere was suitable for mercury oxidation under the conditions from this paper. The percentage of Hg^{2+} was higher under the oxy atmosphere than that during combustion in air atmosphere. NO, HCl and SO_2 enhanced mercury oxidation under oxy-coal combustion.

Larger H_2O concentration under the oxy atmosphere promoted mercury oxidation compared with that under the air atmosphere. Different types of coal also have some influence on mercury oxidation due to the different content of S and Cl in the coal.

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NOMENCLATURE

CN: Chinese bituminous coal; US: American bituminous coal; CN Air: Chinese bituminous coal under air combustion; CN Oxy: Chinese bituminous coal under oxy combustion; US Air: American bituminous coal under air combustion; US Oxy: American bituminous coal under oxy combustion; FC_{ar}: Fixed carbon; V_{ar}: Volatile matter; A_{ar}: Ash; M_{ar}: Moisture; LOI: Loss of incineration.

REFERENCES

Agarwal, H., H. G. Stenger, et al. (2006). "Effects of H2O, SO2, and NO on homogeneous Hg oxidation by Cl2." Energy & Fuels 20(3): 1068-1075.

Buhre, B., L. Elliott, et al. (2005). "Oxy-fuel combustion technology for coal-fired power generation." Progress in energy and combustion science 31(4): 283-307.

Contreras, M., F. García-Frutos, et al. (2013). "Oxy-fuel combustion effects on trace metals behaviour by equilibrium calculations." Fuel 108: 474-483.

Duan, L., H. Sun, et al. (2014). "Coal combustion characteristics on an oxy-fuel circulating fluidized bed combustor with warm flue gas recycle." Fuel 127: 47-51.

Duan, L., C. Zhao, et al. (2009). "Sulfur evolution from coal combustion in O2/CO2 mixture." Journal of Analytical and Applied Pyrolysis 86(2): 269-273.

Fernández-Miranda, N., M. A. Lopez-Anton, et al. (2014). "Effect of oxy-combustion flue gas on mercury oxidation." Environmental science & technology 48(12): 7164-7170.

Font, O., P. Córdoba, et al. (2012). "Fate and abatement of mercury and other trace elements in a coal fluidised bed oxy combustion pilot plant." Fuel 95: 272-281.

Galbreath, K. C. and C. J. Zygarlicke (2000). "Mercury transformations in coal combustion flue gas." Fuel Processing Technology 65: 289-310.

Gharebaghi, M. (2009). Assessment of fate of mercury in oxy-coal combustion. 1st oxyfuel combustion conference, Cottbus, Germany.

Gharebaghi, M., K. Hughes, et al. (2011). "Mercury speciation in air-coal and oxy-coal combustion: A modelling approach." Proceedings of the Combustion Institute 33(2): 1779-1786.

Hecht, E. S., C. R. Shaddix, et al. (2012). "Effect of CO2 and steam gasification reactions on the oxy-combustion of pulverized coal char." Combustion and Flame 159(11): 3437-3447.

Hu, S., D. Zeng, et al. (2011). Effects of Moisture on Char Burnout During Warm-Recy-cle Oxy-Coal Combustion. 2011 International Pittsburgh Coal Conference.

Hu, S., D. Zeng, et al. (2011). Effects of Moisture on Char Burnout during Warm-Recycle Oxy-Coal Combustion. 2011 International Pittsburgh Coal Conference.

Jia, L., Y. Tan, et al. (2012). "Commissioning of a 0.8 MWth CFBC for oxy-fuel combustion." International Journal of Greenhouse Gas Control 7: 240-243.

Laudal, D. L., T. D. Brown, et al. (2000). "Effects of flue gas constituents on mercury speciation." Fuel processing technology 65: 157-165.

Lee, S. J., Y.-C. Seo, et al. (2006). "Speciation and mass distribution of mercury in a bituminous coal-fired power plant." Atmospheric Environment 40(12): 2215-2224.

Li, H., C.-Y. Wu, et al. (2013). "Impact of SO2 on elemental mercury oxidation over CeO2–TiO2 catalyst." Chemical Engineering Journal 219: 319-326.

Lupiáñez, C., I. Guedea, et al. (2013). "Experimental study of SO2 and NOx emissions in fluidized bed oxy-fuel combustion." Fuel Processing Technology 106: 587-594.

McCauley, K., H. Farzan, et al. (2009). "Commercialization of oxy-coal combustion: Applying results of a large 30MWth pilot project." Energy Procedia 1(1): 439-446.

Mitsui, Y., N. Imada, et al. (2011). "Study of Hg and SO3 behavior in flue gas of oxy-fuel combustion system." International Journal of Greenhouse Gas Control 5: S143-S150.

Moorman, S. and D. McDonald (2011). "Oxy-Coal Combustion for Low Carbon Electric Power Generation." Zaragoza.

Niksa, S., J. J. Helble, et al. (2001). "Kinetic modeling of homogeneous mercury oxidation: the importance of NO and H2O in predicting oxidation in coal-derived systems." Environmental science & technology 35(18): 3701-3706.

Omine, N., C. E. Romero, et al. (2012). "Study of elemental mercury re-emission in a simulated wet scrubber." Fuel 91(1): 93-101.

Roesler, J. F., R. A. Yetter, et al. (1995). "Kinetic interactions of CO, NOx, and HCI emissions in postcombustion gases." Combustion and flame 100(3): 495-504.

Roy, B., L. Chen, et al. (2014). "Nitrogen Oxides, Sulfur Trioxide, and Mercury Emissions during Oxy-fuel Fluidized Bed Combustion of Victorian Brown Coal." Environmental science & technology 48(24): 14844-14850.

Santos, S. (2010). Challenges in Understanding the Fate of Mercury during Oxyfuel Combustion. MEC-7. Strathclyde University, Glasgow, Scotland.

Senior, C. L. and S. A. Johnson (2005). "Impact of carbon-in-ash on mercury removal across particulate control devices in coal-fired power plants." Energy & Fuels 19(3): 859-863.

Senior, C. L., A. F. Sarofim, et al. (2000). "Gas-phase transformations of mercury in coal-fired power plants." Fuel Processing Technology 63(2): 197-213.

Spörl, R., J. Maier, et al. (2014). "Mercury and SO3 Emissions in Oxy-fuel Combustion." Energy Procedia 63: 386-402.

Suriyawong, A. and P. Biswas (2013). Homogeneous Mercury Oxidation under Simulated Flue Gas of Oxy-coal Combustion.

Suriyawong, A., M. Gamble, et al. (2006). "Submicrometer particle formation and mercury speciation under O2-CO2 coal combustion." Energy & Fuels 20(6): 2357-2363.

Suriyawong, A., C. J. Hogan, et al. (2008). "Charged fraction and electrostatic collection of ultrafine and submicrometer particles formed during O2–CO2 coal combustion." Fuel 87(6): 673-682.

Van Otten, B., P. A. Buitrago, et al. (2011). "Gas-phase oxidation of mercury by bromine and chlorine in flue gas." Energy & Fuels 25(8): 3530-3536.

Wall, T., R. Stanger, et al. (2013). "Gas cleaning challenges for coal-fired oxy-fuel technology with carbon capture and storage." Fuel 108: 85-90.

Wall, T., R. Stanger, et al. (2011). "Demonstrations of coal-fired oxy-fuel technology for carbon capture and storage and issues with commercial deployment." International journal of greenhouse gas control 5: S5-S15.

Wang, Y., Y. Duan, et al. (2009). "Experimental study on mercury transformation and removal in coal-fired boiler flue gases." Fuel Processing Technology 90(5): 643-651.

Widmer, N., J. West, et al. (2000). Thermochemical study of mercury oxidation in utility boiler flue gases. The 93rd Annual Meeting, Air&Waste Management Association, Salt Lake City, Utah.

Wu, H., H. Liu, et al. (2013). "Experimental study of homogeneous mercury oxidation under O2/CO2 atmosphere." Proceedings of the Combustion Institute 34(2): 2847-2854.

Yang, H., Z. Xu, et al. (2007). "Adsorbents for capturing mercury in coal-fired boiler flue gas." Journal of Hazardous Materials 146(1): 1-11.

Yokoyama, T., K. Asakura, et al. (2000). "Mercury emissions from a coal-fired power plant in Japan." Science of the total environment 259(1): 97-103.

Yu, X. and H. Qu (2013). "The role of China's renewable powers against climate change during the 12th Five-Year and until 2020." Renewable and Sustainable Energy Reviews 22: 401-409.

Zhuang, Y., J. Laumb, et al. (2007). "Impacts of acid gases on mercury oxidation across SCR catalyst." Fuel Processing Technology 88(10): 929-934.