Hindawi Publishing Corporation
Journal of Combustion
Volume 2013, Article ID 749321, 6 pages
http://dx.doi.org/10.1155/2013/749321

Research Article

N_2O and NO Emissions from CFBC Cofiring Dried Sewage Sludge, Wet Sewage Sludge with Coal and PE

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Received 28 February 2013; Revised 2 May 2013; Accepted 7 May 2013

Academic Editor: Constantine D. Rakopoulos

Experiments on cofiring dried sewage sludge, wet sewage sludge with coal and polyethylene (PE) were carried out on a pilot scale 0.15MWt circulating fluidized bed combustion (CFBC) plant, and the influence of furnace temperatures, cofiring rates on N_2O and NO emissions was investigated. Temperature is an effective parameter influencing N_2O emission, and higher temperature leads to significant N_2O reduction and decrease of conversion ratio of fuel-N to N_2O. Increasing in cofiring rates leads to higher nitrogen content in the mixed fuel, which could result in higher NO and N_2O emissions from combustion. With more sewage sludge addition, higher NO but lower N_2O emissions are observed. N_2O emission from cofiring wet sewage sludge with coal is higher than that from cofiring dried sewage sludge with coal and PE, and fuel-N conversion ratio to N_2O and NO is much higher in cofiring wet sewage sludge with coal than that in cofiring dried sewage sludge with coal and PE.

1. Introduction

Vast quantities of sewage sludge are produced as by-product of wastewater treatment in recent years, and the production is expected to rise significantly [1]. Meanwhile, huge quantities of plastic waste are produced due to the ever-increased consumption of plastic all over the world. So much sewage sludge and plastic waste disposal have posed a very serious environmental challenge, and much attention has been paid on this problem.

Volatile contents of sewage sludge as dry ash-free basis are generally higher than 80% [2–4], with heating value similar to that of brown coal, which indicates that sewage sludge could be incinerated with the advantage of thermal recycling and volume reduction [1, 4, 5]. But the low heating value of the sewage sludge is usually very low, because of the high water content in it. Therefore, supplementary fuel is required to ensure stable combustion and burnout. Coal and plastic waste have much higher heating value compared with sewage sludge and is suitable for cofiring with sewage sludge to provide supplementary energy [4, 6]. Circulating fluidized bed combustion (CFBC), as an established technique, is feasible to deal with these waste materials, with the advantages of burning a wide variety of solid fuels and low emissions [7].

However, CFBC emits much N_2O because of its low combustion temperature [8]. In addition, nitrogen content in the sewage sludge is generally in the range of 4–8%, much higher than that in the coal [9, 10], and fuel-N is the main source of NO and N_2O emissions at low combustion temperatures [11]. As a result, there is a high potential for N_2O and NO emissions with sludge combustion in CFBC. It is reported [4] that N_2O emissions were in the range of 300–700 mg/m^3 (std., dry basis) with CFBC cofiring wet sewage sludge with coal. Many intensive researches have been carried out on N_2O and NO emission characteristics from sludge combustion, and detailed information can be found in the work of Werther and Ogada work [1]. But the work undertaken was mainly based on the cofiring of coal with sludge; the knowledge about cofiring sludge with plastic waste is limited. In this work, cofiring of dried sewage sludge and wet sewage sludge with PE on CFBC was conducted. To compare N_2O and NO emissions from cofiring sewage sludge with PE, cofiring sewage sludge with coal was also studied.

2. Experiments

2.1. CFBC Pilot Plant. The investigations were conducted in a pilot-scale CFBC plant. The experimental setup is shown in Figure 1. It includes combustion system, pressure and temperature measuring system, flue-gas sampling, and analysis system.

The combustion system was composed of a furnace with an inside diameter of 300 mm and height of 6000 mm (from the air distributor to the top), a cyclone, a vertical leg, and a U-valve. The refractory-lined bottom of the furnace was 800 mm in height. The other parts of the furnace, the cyclone, the vertical leg, and the U-valve were all made of high temperature alloy covered with heat insulation material on the outside. Forty kilograms of quartz sand with the size of 0.5–1.0 mm was fed into the furnace as bed material during startup. The thermal input to the furnace with sludge and PE or coal was about $0.15MW_{th}$, corresponding to a fuel-feeding rate of 20–80 kg/h, depending on different cofiring rates. The fuel was fed into the furnace through screw feeder, 890 mm above the air distributor. The primary air was fed into the furnace through the air distributor in the range of 100–250 m^3/h, and no secondary air was supplied. Compressed air at atmosphere temperature was used as fluidizing air of the U-valve, in the range of 8–15 m^3/h.

During cofiring dried sewage sludge with coal and PE, the vertical temperature profiles in the furnace were adjusted through regulating the depth of a water tube inserted into the furnace from the top of the furnace. The water tube was 4000 mm in length and 51 mm in outside diameter. But during cofiring wet sewage sludge with coal, the water tube in the furnace was removed to reduce heat loss. During cofiring dried sewage sludge with coal and PE, cofiring wet sewage sludge with coal, the gas concentration of H_2O, SO_2, CO, CO_2, NO, and N_2O was continuously analyzed with an on-line gas analyzer (GasMet DX-3000), and the gas-sampling nozzle was at the exit of the cyclone. Oxygen concentration in flue gas was analyzed with a Zr-type probe. Main operation parameters were recorded in a computer at the interval of 15 seconds. Gas analysis data were stored at an interval of 60 seconds.

2.2. Characteristics of the Sewage Sludge, Coal, and PE. Polyethylene (PE) powder, with average diameter between 2 mm and 3 mm and low heat value of 46.30 MJ/kg, was used to simulate plastic waste. The analysis data of PE, dried sewage sludge, wet sewage sludge, and coal is presented in Table 1. The properties of wet sewage sludge in Table 1 are the average of 4 samples of wet sewage sludge, as in Table 2. The water content in dried sewage sludge (as received basis) is as low as 7.4%, and low heating value is about 12.8 MJ/kg. The water content in wet sewage sludge is about 76.3% (as received basis), and the low heating value is only about 0.64 MJ/kg. The dried sewage sludge is in the form of powder with sizes between 0.1 mm and 1.7 mm. The ash compositions of dried sewage sludge and coal are shown in Table 3. Attention should be paid to the fact that CaO content in the dried sewage sludge is as high as 10%. In some tests, wet sewage sludge was used, and in other tests, dried sewage sludge with water injection through a nozzle at the point 150 mm above the fuel-feed point during the experiments. Dried sewage sludge was mixed with PE or coal before its addition into the furnace, and the wet sewage sludge was added to the furnace at the top of the furnace, through a pump.

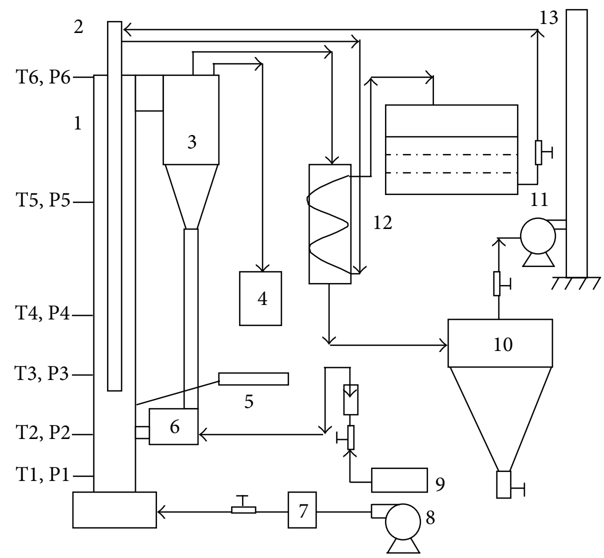

Figure 1: Test facilities of the CFBC pilot: 1, furnace; 2, water tube; 3, cyclone; 4, gas analyzer; 5, fuel screw feeder; 6, U-valve; 7, primary air meter; 8, forced draft fan; 9, air compressor; 10, bag filter; 11, induced draft fan; 12, economizer; 13, stack; T1–T6, thermocouples; P1–P6, pressure taps.

2.3. Experiment Conditions. In the cofiring of dried sewage sludge with coal and PE, the furnace temperatures were in the range of 964–1184 K, and the cofiring rates were in the range of 50%–100%. The water in the simulated wet sewage sludge was 30%, by injection of water. The water content is defined as the total water of the added and that in the sludge divided by the mass of sludge and water. Cofiring rate is defined as the heat input with the sewage sludge divided by the total heat input with sewage sludge and PE or coal. In the cofiring of wet sewage with coal, the furnace temperature was 1187 K. Because the low heating value of wet sewage sludge is too low, cofiring rate is not used in cofiring wet sewage sludge with coal. In the cofiring of wet sewage sludge and coal, the water content in the sludge is 82% (through addition of water to the original wet sewage sludge), the sludge flow rate is 47.2 kg/h, and coal flow rate is 23.1 kg/h. All gas emissions presented in this paper are normalized to dry gas with an oxygen concentration of 6%, at 273 K and 101.3 kPa. In this paper, the oxygen concentration in the flue gas was controlled in the range of 3.3% to 3.6% in all tests.

3. Results and Discussion

3.1. Influence of Furnace Temperatures on N_2O and NO Emissions. The furnace temperature is an effective parameter influencing N_2O emission. Raising the furnace temperature

Table 1: Properties of sewage sludge and coal.

	Coal	Dried sewage sludge	Wet sewage sludge	PE
Ultimate analysis (wt%, dry ash free basis)				
Carbon	83.21	54.96	53.44	85.71
Hydrogen	4.55	6.84	7.75	14.29
Oxygen	9.48	26.81	29.63	
Sulfur	1.52	3.24	3.01	
Nitrogen	0.84	8.15	6.17	
Chlorine	0.04	0.48	0.48	
Calcium	0.36	4.37	4.10	
Ca/(S + 0.5Cl) molar ratio	0.19	1.01	1.02	
LHV (MJ/kg)	25.87	12.81	0.64	46.34
Proximate analysis (wt%, as received basis)				
Moisture	4.54	7.40	76.28	—
Ash	15.10	35.16	11.70	—
Volatile	24.60	47.40	11.67	—
Fixed carbon	55.76	10.04	0.36	—

Table 2: Properties of wet sewage sludge.

Sample	1	2	3	4	Average
Ultimate analysis (wt%, dry ash free basis)					
Carbon	58.9	50.4	52	52.4	53.4
Hydrogen	8.47	7.23	7.72	7.56	7.55
Oxygen	21.6	32.8	31.9	32.2	29.6
Sulfur	3.42	3.67	2.61	2.35	3.01
Nitrogen	7.53	5.89	5.74	5.52	6.17
Proximate analysis (wt%, as received basis)					
Moisture	72.9	78.8	77.4	76	76.3
Ash	15	10.1	11	10.7	11.7
Volatile	11.7	10.7	11.2	13	11.7
Fixed carbon	0.41	0.38	0.37	0.26	0.36
LHV (MJ/kg)	0.96	0.26	0.48	0.85	0.64

Table 3: Composition of the ash of coal and sewage sludge.

Items	Coal (wt%)	Sewage sludge (wt%)
SiO_2	58.72	36.33
Al_2O_3	21.26	21.08
Fe_2O_3	11.22	9.17
CaO	2.7	10
MgO	0.54	3.41
SO_3	1.25	0.87
TiO_2	0.84	3.49
K_2O	2.05	6.85
Na_2O	0.12	2.01
P_2O_5	0.22	2.08

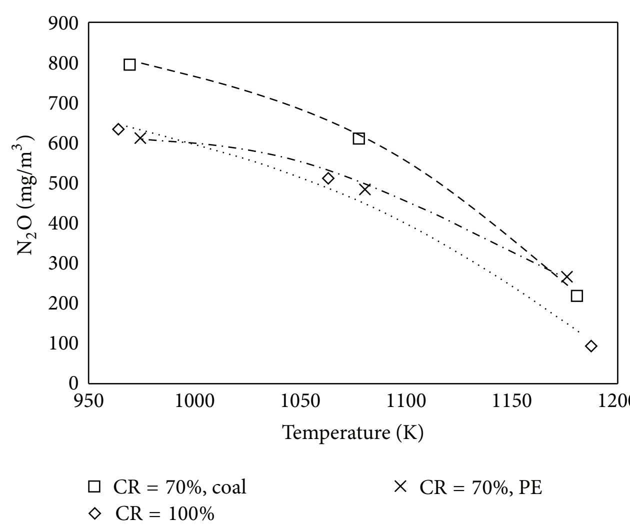

Figure 2: Influence of furnace temperature on N_2O emission.

leads to significant N_2O reduction during the combustion of sludge and coal [9, 12, 13], and N_2O concentrations decreased from 560 mg/m^3 to less than 110 mg/m^3 as the freeboard temperature increased from 1117 K to 1149 K during wet sludge incineration. The same trend in this study was also found, as in Figure 2. As the furnace temperature increases from about 973 K to about 1173 K, N_2O emission decreases from 612 mg/m^3 to 266 mg/m^3 for the cofiring rate of 100% and decreases from 794 mg/m^3 to 218 mg/m^3 for the cofiring rates of 70% with coal, from 674 mg/m^3 to 94 mg/m^3 for the cofiring rate of 70% with PE. The influence of furnace temperature on the conversion ratio of fuel-N to N_2O is shown in Figure 3, and it is clear that an increase in furnace temperature leads to the reduction of conversion ratio of fuel-N to N_2O.

Influence of the furnace temperatures on NO emission is shown in Figure 4. For the test runs with cofiring rate of 100%, an increase in furnace temperature results in a decrease of NO emission and of a conversion ratio of fuel-N to NO, as shown in Figure 5. But for the test runs of cofiring sewage sludge

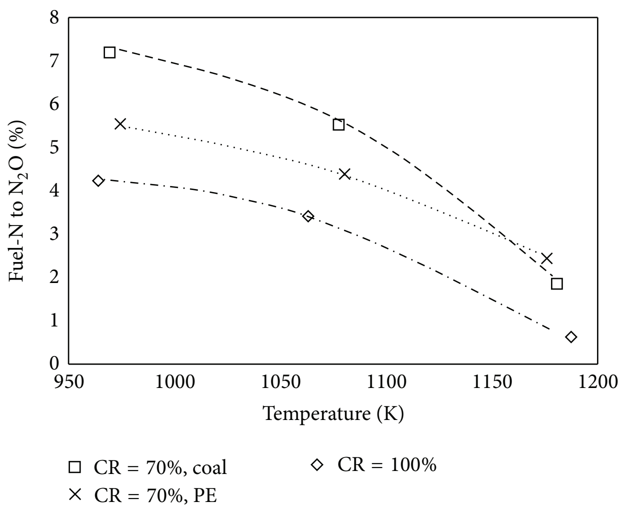

FIGURE 3: Influence of furnace temperature on conversion ratio of fuel-N to N_2O.

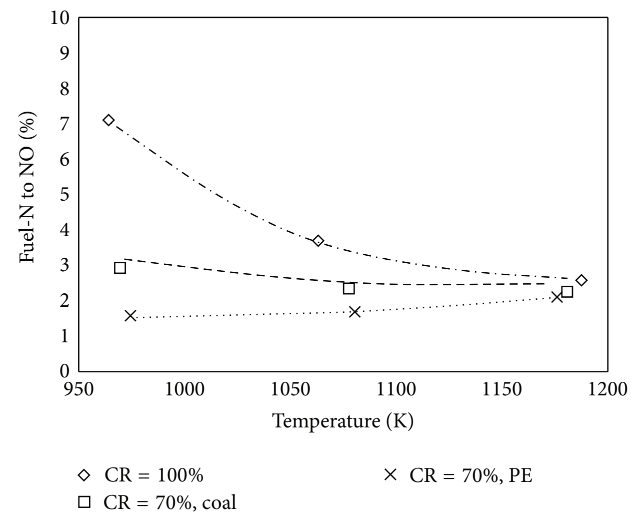

FIGURE 5: Influence of furnace temperatures on conversion ratio of fuel-N to NO.

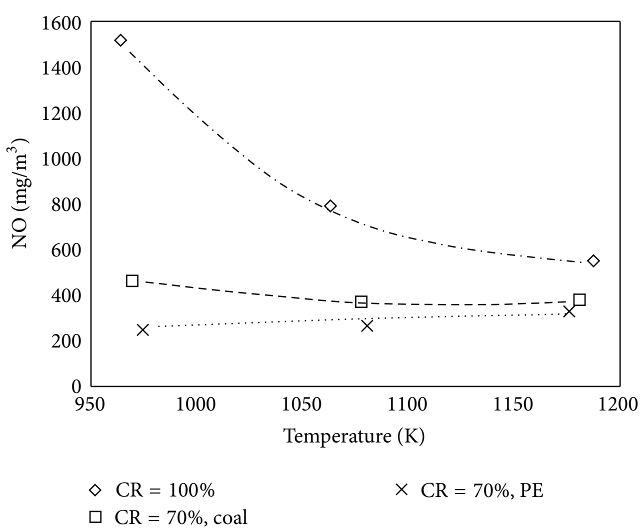

FIGURE 4: Influence of furnace temperatures on NO emission.

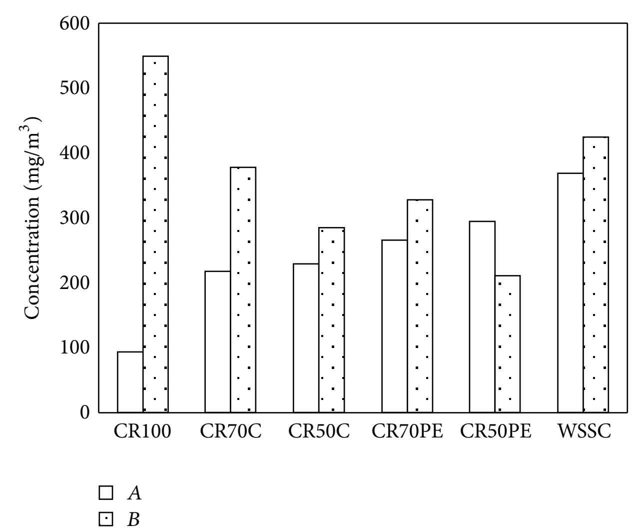

FIGURE 6: Influence of cofiring rates on N_2O emission. *A:* N_2O; *B:* NO.

with coal and PE, furnace temperature is not an important parameter influencing NO emissions.

3.2. Influence of Cofiring Rates on N_2O and NO Emissions. Nitrogen content in the mixed fuel increases with the rising of cofiring rates, which presents a higher potential for N_2O and NO emissions [4, 11], and the influence of cofiring rate on N_2O and NO emissions was studied, and the test conditions were in Table 4, and the furnace temperature was in the range of 1180 K and 1190 K.

As in Figure 6, when the cofiring rates increase from 50% to 100%, NO emission increases from about 211 mg/m^3 to 551 mg/m^3 with cofiring of PE and increases from 266 mg/m^3 to 551 mg/m^3 with cofiring of coal, and similar results from cofiring sludge with pulverized coal were also reported [1]. But with the increase of cofiring rates from 50% to 100%, N_2O emission decreases from 295 mg/m^3 to 93 mg/m^3 for cofiring of PE and decreases from 229 mg/m^3 to 93 mg/m^3 for cofiring of coal, but this observation is different from the work of Philippek and Werther [4], in which significant N_2O emission increasing was observed with more sludge addition to coal firing boiler. For cofiring of sewage sludge with coal and PE, increase in cofiring rates leads to lower conversion ratio of fuel-N to N_2O, but there is not an apparent tendency about influence of cofiring rate on conversion ratio of fuel-N to NO. As in Figure 6, N_2O emission from cofiring wet sewage sludge with coal is 370 mg/m^3, much higher than that from cofiring dried sewage sludge with coal and PE, at the range of 93–295 mg/m^3. As in Figure 7, conversion ratio of fuel-N to N_2O and NO in cofiring wet sewage sludge with coal is 14% and 11%, respectively, but in cofiring dried sewage

Table 4: The co-firing rate test conditions.

Test number	Co-firing rate (%)	Coal (%)	PE (%)	Dried sewage sludge (%)	Wet sewage sludge (%)
CR100	100	0	0	100	
CR70C	70	30	0	70	
CR50C	50	50	0	50	
CR70PE	70	0	30	70	
CR50PE	50	0	50	50	
WSSC	0	50 (mass)	0	0	50 (mass)

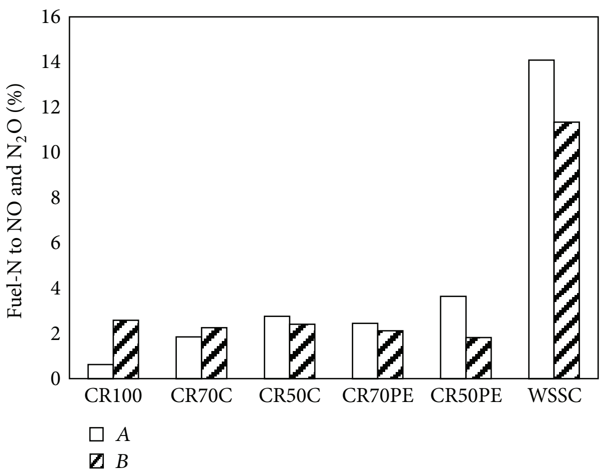

Figure 7: Influence of cofiring rate on NO emission. *A:* N_2O; *B:* NO; CR100: CR no. 100%; CR70C: CR no. 70%, coal; CR50C: CR no. 50%, coal; CR70PE: CR no. 70%, PE; CR50PE: CR no. 50%, PE; WSSC: wet sewage sludge and coal.

sludge, conversion ratio of fuel-N to N_2O and NO is much lower, only 0.6%–3.6% and 1.8%–2.6%, respectively.

In the process of cofiring sewage sludge with PE and coal, CaO plays an important role in influencing N_2O and NO emissions. Because of the high Ca content in the sludge ash and the high ash content in the sludge, CaO concentration in the furnace is higher when the cofiring rates increase, and CaO can catalyze the reactions of NO formation and N_2O reduction [4, 14].

As in Figure 7, increase of cofiring rates leads to an increase in fuel nitrogen conversion ratios to NO and a decrease in ratios of fuel nitrogen conversion to N_2O. The catalytic reactions enhance the NO emission, as shown in Figure 7, and are the dominant factor leading to the decrease in N_2O emission.

4. Conclusion

Through cofiring of dried sewage sludge, wet sewage sludge with coal and PE on the pilot scale $0.15MW_{th}$ CFBC plant, the following conclusions were deduced:

(1) the furnace temperature is an effective parameter influencing N_2O emission, and high temperature helps to enhance N_2O decomposition;

(2) there is a strong dependence of N_2O and NO emissions on cofiring rates, and rise of cofiring rates leads to lower N_2O emission but higher NO emission. And increase in cofiring rates also results in the reduction of conversion ratio of fuel-N to N_2O;

(3) N_2O emission from cofiring wet sewage sludge is much higher than that from cofiring dried sewage sludge with coal and PE, and fuel-N conversion ratio to N_2O and NO in cofiring wet sewage sludge with coal is much higher than that in cofiring dried sewage sludge with coal and PE.

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