**Establishment of an Environmental Control Technology Laboratory
with a Circulating Fluidized-Bed Combustion System**

Quarterly Technical Progress Report

April 1 – June 30, 2005

Wei-Ping Pan, Andy Wu, and John T. Riley

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Institute for Combustion Science and Environmental Technology
Western Kentucky University
2413 Nashville Road
Bowling Green, KY 42101

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ABSTRACT

This purpose of this report is to present the progress made on the project “Establishment of an Environmental Control Technology Laboratory (ECTL) with a Circulating Fluidized-Bed Combustion (CFBC) System” during the period April 1, 2005 through June 30, 2005. The following tasks have been completed. First, the new Combustion Laboratory was occupied on June 15, 2005, and the construction of the Circulating Fluidized-Bed (CFB) Combustor Building is in the final painting stage. Second, the fabrication and manufacturing contract for the CFBC Facility was awarded to Sterling Boiler & Mechanical, Inc. of Evansville, Indiana. Sterling is manufacturing the assembly and component parts of the CFBC system. The erection of the CFBC system is expected to start September 1, 2005. Third, mercury emissions from the co-firing of coal and chicken waste was studied experimentally in the laboratory-scale simulated fluidized-bed combustion facility. The experimental results from this study are presented in this report. Finally, the proposed work for the next quarter is described.

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1. EXECUTIVE SUMMARY

The following tasks have been completed this quarter (April 1, 2005 through June 30, 2005). First, the renovation of new Combustion Laboratory has been completed, and the Institute for Combustion Science and Environmental Technology (ICSET) started to occupy the new Combustion Laboratory on June 15, 2005. Construction of the Circulating Fluidized-Bed Combustor (CFBC) Building is nearly completed and is in the final painting stage. The expected occupying date is at the beginning of August 2005. Second, the contract for fabricating and manufacturing the assembly and component parts of the CFBC Facility was awarded to Sterling Boiler & Mechanical, Inc. of Evansville, Indiana. Currently Sterling is purchasing the necessary materials and manufacturing the parts of CFBC system based on the design drawings. All machine work will be completed before the middle of September 2005. Third, the mercury emissions from the co-firing of chicken waste and coal with different blend ratios has been investigated in the laboratory-scale simulated fluidized-bed facility. The mercury emissions in both the solid and gas phases were measured. Finally, the work planned for the next quarter is introduced, and the reasons for delays incurred in some of the tasks are discussed.

2. EXPERIMENTAL

2.1. Renovation of Combustion Laboratory and Construction of CFBC Building

The renovation of the Combustion Laboratory has been completed. On June 15, 2005, the Institute for Combustion Science and Environmental Technology began to occupy the new Combustion Laboratory. The new laboratory includes several offices, a machine shop, a library, a conference room, an instrument room, an analytical room, a coal preparation room, a model display room, a loading area, and a control room. Figure 1 shows several photographs of the new Combustion Laboratory. The construction of the CFBC Building is nearly completed. Currently, the construction efforts are focused on painting, internal arrangement, and pavement of outside area. Figure 2 is a photograph of the newly erected CFBC Building. The expected occupying date is scheduled for the beginning of August 2005. The erection of the CFBC system is expected to begin in the middle of September 2005.

2.2. Design and Manufacture of the CFBC Facility

Library

Office

Hallway

Conference Room

Analytical Room

Instrument Room

Figure 1. Photographs of the new Combustion Laboratory

Figure 2. Photographs of the nearly completed CFBC Building

Based on qualifications, price, and schedule, Sterling Boiler & Mechanical, Inc. was selected as the contractor to fabricate and erect the CFBC Facility. Currently, Sterling is purchasing the necessary materials and manufacturing the parts of the CFBC system based on the design drawings. During this period, the following progress has been made on the design of the CFBC Facility.

- a. The detailed structure design required to avoid the twist and displacement in the horizontal direction has been finalized, and the drawings for this structure have been released to the manufacturer.
- b. Based on Sterling's comments, the rotation direction of the gas streams in the primary and secondary cyclones have been changed.
- c. In order to control the solid circulation flow, the loop seal was modified by adding a horizontal air injection nozzle. By controlling the air flow rate through the nozzle, the solid circulation flow rate can be easily and accurately adjusted.

- d. The design of the bunker support system, which allows the change of solid weight inside the bunkers to be monitored, has been finalized. Therefore, the solid (coal, limestone, and waste materials) feed rate can be acquired on-line.

2.3 Experimental Study on Mercury Emissions from the Co-firing of Coal and Chicken Waste

2.3.1. Background on Mercury Emissions from the Co-Firing of Chicken Waste and Coal

The U.S. Environmental Protection Agency (EPA) set up a regulation to limit the emissions of mercury from coal-fired power plants in March 2005. Based on this new regulation, mercury emissions should be reduced 20% by 2010, and 70% by 2018. Besides installing the necessary air pollution control devices (APCD) or injecting sorbents to capture mercury, selecting low mercury content fuels is an additional option. Since chicken waste has a certain heating value and its mercury content is very low, the co-combustion of chicken waste and coal should decrease the emission of mercury. At the same time, the chlorine content in chicken waste is much higher than that of coal. The existence of chlorine is considered to be beneficial for converting the elemental mercury to oxidized mercury. The latter is more easily captured by APCD because of its solubility and adsorption onto solid particles. Therefore, the addition of chicken waste can potentially reduce the emissions of mercury from coal combustion significantly.

The objective of this work is to investigate the mercury emissions from co-firing chicken waste with coal at atmospheric pressure in a laboratory-scale simulated fluidized-bed combustor (FBC). The mercury distribution in the particulate and gaseous phases will be measured experimentally.

2.3.2. Experimental Setup and Mercury Emission Measurement

The laboratory-scale simulated FBC used in this study was described in a previous report. In this report, only the method for measuring mercury emissions is introduced.

PSA analytical semi-continuous emissions monitoring (SCEM) system was used in this study to analyze the gaseous mercury and its speciation in the flue gas. Figure 3 shows a schematic diagram of the SCEM system. Mercury SCEM consists of four major components: (1) A probe, filter, and pump module. (2) Heated Teflon sample lines, which are normally maintained at 200°C and are considered necessary to prevent losses of mercury along the sample lines, keep the speciation the same as that in the flue gas duct, and reduce condensation of acid

gases. (3) The mercury conversion system. (4) The analyzer and data system. The Quality Assurance and Quality Control (QA/QC) procedures are also shown in Figure 3.

Figure 3. The schematic diagram of mercury SCQM system and QA/QC procedures

In each test, the bottom ash discharged from the dense zone and the fly ash captured by the cyclone were collected. The mercury content in the fly ash and bottom ash was analyzed with the LECO AMA-254.

2.3.3 Bed Materials and Testing Conditions

Due to its availability, abundance, inert nature and high melting point, silica sand was selected as the bed material in the laboratory-scale simulated FBC. Silica sand was sized in the range of 0.6 to 0.85 mm by sieving. The static bed height was maintained at about 6" inches. The detailed testing procedure in this study was similar to what was described in the previous report.

Four sets of combustion tests were performed: (1) combustion of coal alone. (2) co-combustion of 10% chicken waste with 90% coal. (3) co-combustion of 25% chicken waste with 75% coal. (4) co-combustion of 50% chicken waste with 50% coal. All percentages in mixtures of chicken waste and coal are based on weight. The bed temperature was maintained in the range of 830~860 °C. The oxygen concentration was maintained in the range of 6.8~7.4%.

3. RESULTS AND DISCUSSION

3.1. Analysis of Chicken Waste and Coal Mixture

Table 1. Characteristics of chicken waste and coal mixture

Fuel	Moisture (wt %)	Ash (wt %)	Volatile Matter (wt %)	C (wt %)	H (wt %)	O (wt %)	N (wt %)	S (wt %)	Hg (ppm)	Cl (ppm)	Heating Value (Btu/lb)
CW	11.32	27.59	50.79	28.18	4.98	3.39	35.00	0.86	<0.01	11639	5074
Coal	2.62	9.64	36.56	71.31	5.28	1.43	8.82	3.52	0.13	1537	12948
CW/ Coal in 1:1	6.97	18.62	43.68	49.75	5.13	2.41	21.91	2.19	0.07	6588	9011
CW/ Coal in 1:3	4.80	14.13	40.12	60.53	5.21	1.92	15.37	2.89	0.10	4063	10980
CW/ Coal in 1:9	3.49	11.44	37.98	67.00	5.25	1.63	11.44	3.25	0.12	2547	12161

Based on the proximate and ultimate analysis of both chicken waste and coal, the characteristics of the mixtures of chicken waste and coal with different blend ratios were calculated and are presented in Table 1.

3.2 Mercury Bonded with Particulate Phase

During each test, the fly ash was collected by a mini cyclone located at the outlet of the laboratory-scale simulated FBC, while the bottom ash was discharged from the dense zone of the FBC directly. The collected fly ash and bottom ash samples were analyzed by a LECO AMA-254 to determine the mercury content. Table 2 lists the mercury content in the fly ash and bottom ash. It was found that the content of mercury in the bed ash was negligible. This is because all mercury compounds exist as elemental mercury in the gas phase under such high temperature conditions. The content of mercury in the fly ash for co-firing of chicken waste with coal was higher than that of coal alone. The mercury (Hg) content in the fly ash increases with the increase of chicken waste in the blend. The main reason is that chicken waste contains high chlorine. It is widely known that the chlorine, which is transformed to hydrogen chlorine during the combustion process, is beneficial to the conversion of Hg^0 to Hg^{2+} in the flue gas, and Hg^{2+} is much more easily adsorbed and captured by the fly ash. Another reason is that chicken waste has

a higher ash content, and some minerals could play a role in absorbing the mercury in the gas phase. By assuming all ash contained in the fuel was converted into fly ash, the total mercury in particulate phase based on one unit fuel was calculated and listed in Table 2.

Table 2. Mercury and carbon contents in the fly ash and bottom ash

Sample name	Mercury in fly ash ppmw	Mercury in bottom ash ppmw	Total mercury in particulate phase ng/kg fuel*	Total mercury in particulate phase $\mu\text{g/MMBtu}^*$
100%coal	0.11	0.004	10.644	373
10%CW+90%coal	0.16	0.003	18.304	683
25%CW+75%coal	0.22	0.003	31.086	1284
50%CW+50%coal	0.35	0.005	65.415	3293

* Assuming all ash of fuel converts into in fly ash during the combustion process.

Figure 4. Effect of chlorine content on mercury content in fly ash

The data indicates that the mercury content in the particulate phase increases substantially with the increase of chicken waste in the blend. In fact, the ash generated by coal during the combustion process was much coarser than that of chicken waste. This implies that the fraction of fly ash would increase with the increase of the chicken waste in the blend. Therefore, the actual mercury content in the particulate phase for high chicken waste ratio blends should be much higher than that for low chicken waste ratio blends or for coal alone. Similar calculations

were made based on the fuel heating value. The calculated results, which are listed in Table 2 also, show that the amount of mercury remaining in the particulate phase increases with the increase of chicken waste in the blend. Based on these facts, it can be concluded that the co-firing of chicken waste with coal can decrease the emission of mercury dramatically. Figure 4 shows the effect of chlorine in the fuel on the mercury content in the fly ash. Note that there is a significant increase in the mercury content of the fly ash with increasing the chloride content in the fuel.

In this study, the effect of secondary air on mercury emissions was also investigated. Table 3 shows the variation in the mercury content in fly ash with/without secondary air. It was found that secondary air improved the capture of mercury by fly ash. The mercury content in fly ash for co-firing with secondary air was about 2 times that of co-firing without secondary air. This is a result of the fact that the secondary air provided a good mixture between solids and flue gas, a high turbulence level, and a high solid concentration in the freeboard. High solid concentration in the freeboard supplies more surface area to absorb mercury. The secondary air has very little effect on the mercury content in bottom ash.

Table 3. Effects of secondary air on the mercury content in fly ash and bottom ash

-----	50% chicken litter / 50% coal			
	Without secondary air		With secondary air	
	Bottom ash	Fly ash	Bottom ash	Fly ash
Mercury (ppm)	0.003	0.16	0.005	0.35

3.3 Mercury Emission in the Gas Phase

The mercury emissions in the gas phase were measured on-line by the SCEM system during the test. Table 4 presents a summary of mercury concentrations in the gas phase for all tests. Both total mercury (including the elemental and oxidized mercury) and elemental mercury in the gas phase for coal alone are higher than those for co-firing of chicken waste with coal. Total mercury and elemental mercury decreased with increasing the amount of chicken waste in the blend.

Table 4. Elemental mercury and total mercury in the gas phase

	Coal alone	10%CW/90%coal	25%CW/75%coal
Total gaseous mercury (ng/Nm ³)	10000	6333	5672
Gaseous elemental mercury (ng/Nm ³)	7647	4100	3329
Ratio of elemental mercury to total gaseous mercury	0.765	0.647	0.587

Figure 5. Ratio of elemental mercury to total mercury with increasing amounts of chicken waste

The ratio of elemental mercury to total mercury in the gas phase is also presented in Table 4. Figure 5 shows the ratio of gaseous elementary mercury to total gaseous mercury for the different blending ratios of chicken waste with coal. It was found that the emission of gaseous elementary mercury from the combustion of coal alone accounted for about 76.4 wt.% of the total gaseous mercury. The ratio of elemental mercury to total mercury in the gas phase decreases with an increase of the chicken waste in the blend. That means that the oxidized mercury, which is easily removed by APCD, increases with the addition of the chicken waste.

Therefore, the chicken waste can be very beneficial to the reduction of mercury emissions for the co-firing of coal and chicken waste. The explanation for this result is as follows: First of all, chicken waste contains very little mercury ($<0.01\text{ppmw}$), therefore, the addition of chicken waste reduces the mercury content in the blend significantly, as shown in Table 1. Therefore, the total input of mercury based on the mass or heating value of the fuel decreases with an increase in the amount of chicken waste in the blend. On the other hand, hydrogen chlorine, from high chlorine content in chicken waste during the combustion process, leads to the adsorption of more mercury by the fly ash and conversion of elemental mercury to oxidized mercury.

3.4 Mercury Balance

A mercury mass balance and speciation diagram for all the tests in this study is presented in Figure 6. The mercury mass balance and speciation was performed by comparing the content of mercury in the ash, gaseous elemental mercury, and gaseous oxidized mercury to the total amount of mercury entering the combustor with the fuel. It was found that the mercury adsorbed by the ash accounted for only about 2 wt.% of the total mercury entering the combustor for combustion of coal alone. However, for co-firing of 50 wt.% chicken waste and 50 wt.% coal, the amount of mercury adsorbed by the ash reached up to 35.3 wt.% of the total mercury. This illustrates that the ash from the coal and chicken waste mixture more easily adsorbs mercury, rather than just burning coal.

Figure 6. Mercury balance

4. CONCLUSIONS

During this quarter, the following progress has been made:

- ◆ The renovation of the new Combustion Laboratory is completed and was fully occupied on June 15, 2005. The construction of the CFBC Building is in the final stage.
- ◆ Sterling Boiler & Mechanical, Inc. was selected as the contractor to manufacture all parts of CFBC Facility and install the CFBC system.
- ◆ Based on Sterling's review on the drawings of CFBC Facility, some structures were modified or re-designed.
- ◆ The mercury emissions from the co-firing of chicken waste and coal with different blend ratios has been investigated on a laboratory-scale simulated FBC Facility. The following conclusions can be summarized from the experimental results:
 - Mercury bonded in the particulate phase increases with an increase in the amount of chicken waste in the blend.
 - Total mercury emissions in the gase phase decreases with an increasing ratio of chicken waste in the blend. The ratio of elemental mercury to total mercury in the gas phase decreases with an increase in chicken waste in the blend.
 - Chicken waste is beneficial to decrease mercury emission from co-combustion of coal and chicken waste based on mass or heating value of fuel.
 - Chicken waste decreases mercury emissions due to low mercury and high chlorine contents of the chicken waste.

5. FUTURE WORK AND UPDATED SCHEDULE

5.1 Future Work

During the next quarter, work will focus on the following tasks:

- ✦ Continuously cooperate with Sterling Boiler & Mechanical, Inc. on fabricating all parts of the CFBC Facility.
- ✦ Following the completion of construction of CFBC Building, a laboratory-scale simulated fluidized-bed combustor, a multiphase flow reactor, and several flue gas analyzers will be relocated in the CFBC Building. A laboratory-scale unit for

generating activated carbon using chicken waste will also be installed in the CFBC Building.

- ✦ Identify a contractor to design and install the process control and measurement system for the CFBC Facility.
- ✦ Continue to conduct experiments on the laboratory-scale simulated FBC. The following experiments will also be carried out during the next quarter:
 - ❖ Study conditions for oxidation of hydrogen chloride to chlorine by Deacon reaction in a flue gas atmosphere.
 - ❖ Mercury sorbent evaluation and development.

5.2 Updated Schedule

Based on the current status of the project, the updated schedule for Calendar Year 2005 is shown in Table 5.

Table 5. Updated Schedule for Calendar Year 2005

Task	Updated Schedule
Move into the CFBC Building	Before August 15, 2005
Initiate erection of the CFBC Facility	September 1, 2005
Complete fabrication of component parts of the CFBC Facility	September 15, 2005
Release the contract to a qualified vender for design and installation of the process control and measurement system of CFBC Facility	September 30, 2005
Complete tests for study conditions for oxidation of hydrogen chloride to chlorine by Deacon reaction in a flue gas atmosphere. Complete mercury sorbent evaluation and development.	September 30, 2005
Grand opening of new Combustion Laboratory	October 15, 2005
Complete the installation of bench-scale CFBC Facility	December 30, 2005

ACRONYMS AND ABBREVIATIONS

A	Ash content (wt%)
APCD	Air Pollution Control Device
Btu	British Thermal Unit
C	Carbon content (wt%)
CFB	Circulating Fluidized-Bed
CFBC	Circulating Fluidized-Bed Combustion
Cl	Chlorine content (ppm)
CW	Chicken waste
DOE	U.S. Department of Energy
ECTL	Environmental Control Technology Laboratory
EPA	Environmental Protection Agency
FBC	Fluidized-Bed Combustion
ft	Feet
H	Hydrogen content (wt%)
Hg	Mercury content (ppm)
Hg ⁰	Elemental mercury
Hg ⁺²	Oxidized mercury
ISCET	Institute for Combustion Science and Environmental Technology
lb	pound
M	Moisture (wt%)
N	Nitrogen content (wt%)
O	Oxygen content (wt%)
ppm	parts per million
QA	Quality assurance
QC	Quality control
S	Sulfur (wt%)
SCEM	Semi-continuous Emission Monitor
U.S.	the United States
V	Volatile matter (wt%)

W	Moisture content (%)
wt	Weight

REFERENCES

- [1] Benson S.A., Miller S.J., Laudal D.L., Galbreath K.C. An Overview of Mercury & Studies at the Energy Environmental Research Center. The 15th annual international Pittsburgh Coal Conference. Pittsburgh, PA.
- [2] Saenger M., Werther J., Hanben H. Concentrations and Mass Balance of Mercury in a Fluidized Bed Sewage Sludge Incineration Plant. Proceedings of the 15th International Conference on FBC, Savannah, GA, ASME.
- [3] Liu K.L., Gao Y., Kellie S., Pan Wei-ping, et al. A Study of Mercury Removal in FBC Systems Fired with High Chlorine Coals. Combustion Science and Technology.2001, 164:145-162.
- [4] R.F. Afonso, C.L. Senior. Assessment of mercury emissions from full scale power plants. Proceedings of the EPRI-EPA-DOE-AWMA Mega Symposium and Mercury Conference. Air & Waste Management Association: Pittsburgh, 2001.
- [5] Database of Information Collected in the Electric Utility Steam Generating Unit Mercury Emissions Information Collection Effort, OMB Control No.2060-0396, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards Research Triangle Park, NC.