USE OF COAL DRYING TO REDUCE WATER CONSUMED IN PULVERIZED COAL POWER PLANTS

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ABSTRACT

This is the sixth Quarterly Report for this project. The background and technical justification for the project are described, including potential benefits of reducing fuel moisture, prior to firing in a pulverized coal boiler.

Coal drying experiments were performed with a Powder River Basin coal to measure the effects of fluidization velocity and drying temperature on rate of drying in a batch drying process. Comparisons to computational results using the batch bed drying model show good agreement. Comparisons to drying results with North Dakota lignite at the same process conditions confirm the lignite dries slightly more rapidly than the PRB.

Experiments were also carried out to determine the effects of inlet air humidity on drying rate. The specific humidity ranged from a value typical for air at temperatures near freezing to a value for 30°C air at 90 percent relative humidity. The experimental results show drying rate is strongly affected by inlet air humidity, with the rate decreasing with more humid inlet air. The temperature of the drying process also plays a strong role, with the negative impacts of high inlet moisture being less of a factor in a higher temperature drying process.

Concepts for coal drying systems integrated into a power plant were developed. These make use of hot circulating cooling water from the condenser, steam extraction from the turbine cycle and thermal energy extracted from hot flue gas, in various combinations. Analyses are under way to calculate the effects of drying system design and process conditions on unit performance, emissions, and cooling tower makeup water.

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INTRODUCTION

Background

Low rank fuels such as subbituminous coals and lignites contain significant amounts of moisture compared to higher rank coals. Typically, the moisture content of subbituminous coals ranges from 15 to 30 percent, while that for lignites is between 25 and 40 percent, where both are expressed on a wet coal basis. Please see Appendix A for more details on definitions of coal moisture used in this report.

High fuel moisture has several adverse impacts on the operation of a pulverized coal generating unit. High fuel moisture results in fuel handling problems, and it affects heat rate, mass rate (tonnage) of emissions, and the consumption of water needed for evaporative cooling.

This project deals with lignite and subbituminous coal-fired pulverized coal power plants, which are cooled by evaporative cooling towers. In particular, the project involves use of power plant waste heat to partially dry the coal before it is fed to the pulverizers. Done in a proper way, coal drying will reduce cooling tower makeup water requirements and also provide heat rate and emissions benefits.

The technology addressed in this project makes use of the hot circulating cooling water leaving the condenser to heat the air used for drying the coal (Figure 1). The temperature of the circulating water leaving the condenser is usually about 49°C (120°F), and this can be used to produce an air stream at approximately 43°C (110°F). Figure 2 shows a variation of this approach, in which coal drying would be accomplished by both warm air, passing through the dryer, and a flow of hot circulating cooling water, passing through a heat exchanger located in the dryer. Higher temperature drying can be accomplished if hot flue gas from the boiler or extracted steam from the turbine cycle is used to supplement the thermal energy obtained from

the circulating cooling water. Various options such as these are being examined in this investigation.

Figure 1: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 1)

Figure 2: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 2)

Previous Work

Two of the investigators (Levy and Sarunac) have been involved in work with the Great River Energy Corporation on a study of low temperature drying at the Coal Creek Generating Station in Underwood, North Dakota. Coal Creek has two units with total gross generation exceeding 1,100 MW. The units fire a lignite fuel containing approximately 40 percent moisture and 12 percent ash. Both units at Coal Creek are equipped with low NO_x firing systems and have wet scrubbers and evaporative cooling towers.

The project team performed a theoretical analysis to estimate the impact on cooling water makeup flow of using hot circulating water to the cooling tower to heat the drying air and to estimate the magnitude of heat rate improvement that could be achieved at Coal Creek Station by removing a portion of the fuel moisture. The results show that drying the coal from 40 to 25 percent moisture will result in reductions in makeup water flow rate from 5 to 7 percent, depending on ambient conditions (Figure 3). For a 550 MW unit, the water savings are predicted to range from 1.17×10^6 liters/day (0.3×10^6 gallons/day) to 4.28×10^6 liters/day (1.1×10^6 gallons/day). The analysis also shows the heat rate and the CO₂ and SO₂ mass emissions will all be reduced by about 5 percent (Ref. 1).

Figure 3: The Effects of Coal Moisture on Cooling Tower Makeup Water

A coal test burn was conducted at Coal Creek Unit 2 in October 2001 to determine the effect on unit operations. The lignite was dried for this test by an outdoor stockpile coal drying system. On average, the coal moisture was reduced by 6.1 percent, from 37.5 to 31.4 percent. Analysis of boiler efficiency and net unit heat rate showed that with coal drying, the improvement in boiler efficiency was approximately 2.6 percent, and the improvement in net unit heat rate was 2.7 to 2.8 percent. These results are in close agreement with theoretical predictions (Figure 4). The test data also showed the fuel flow rate was reduced by 10.8 percent and the flue gas flow rate was reduced by 4 percent. The combination of lower coal flow rate and better grindability combined to reduce mill power consumption by approximately 17 percent. Fan power was reduced by 3.8 percent due to lower air and flue gas flow rates. The average reduction in total auxiliary power was approximately 3.8 percent (Ref. 1).

Figure 4: Improvement in Net Unit Heat Rate Versus Reduction in Coal Moisture Content

This Investigation

Theoretical analyses and coal test burns performed at a lignite fired power plant show that by reducing the fuel moisture, it is indeed possible to improve boiler performance and unit heat rate, reduce emissions and reduce water consumption by the evaporative cooling tower. The economic viability of the approach and the actual impact of the drying system on water consumption, unit heat rate and stack emissions will depend critically on the design and operating conditions of the drying system.

The present project is evaluating low temperature drying of lignite and Power River Basin (PRB) coal. Drying studies are being performed to gather data and develop models on drying kinetics. In addition, analyses are being carried out to determine the relative costs and performance impacts (in terms of heat rate, cooling tower water consumption and emissions) of the various drying options, along with the development of an optimized system design and recommended operating conditions.

The project is being carried out in five tasks:

Note: Minor Change in Scope.

The original Task Statements included experiments and analyses for both fluidized bed and fixed bed dryers (see previous Quarterly Reports). After the project was started, it became clear there is no advantage to using fixed bed dryers for this application. For this reason, the technical scope was changed in June 2004 to emphasize fluidized bed drying. The Task Statements in this report reflect this change in emphasis.

Task 1: Fabricate and Instrument Equipment

A laboratory scale batch fluidized bed drying system will be designed, fabricated and instrumented in this task.

Task 2: Perform Drying Experiments

The experiments will be carried out while varying superficial air velocity, inlet air temperature and specific humidity, particle size distribution, bed depth, and in-bed heater heat flux. Experiments will be performed with both lignite and PRB coals.

Task 3: Develop Drying Models and Compare to Experimental Data

In this task, the laboratory drying data will be compared to equilibrium and kinetic models to develop models suitable for evaluating tradeoffs between dryer designs.

Task 4: Drying System Design

Using the kinetic data and models from Tasks 2 and 3, dryers will be designed for 600 MW lignite and PRB coal-fired power plants. Designs will be developed to dry the coal by various amounts. Auxiliary equipment such as fans, water to air heat exchangers, dust collection system and coal crushers will be sized, and installed capital costs and operating costs will be estimated.

Task 5: Analysis of Impacts on Unit Performance and Cost of Energy

Analyses will be performed to estimate the effects of dryer operation on cooling tower makeup water, unit heat rate, auxiliary power, and stack emissions. The cost of energy will be estimated as a function of the reduction in coal moisture content. Cost comparisons will be made between dryer operating conditions (for example, drying temperature and superficial air velocity).

The project was initiated on December 26, 2002. The project schedule is shown in Figure 5.

Figure 5: Project Schedule

EXECUTIVE SUMMARY

Background

Low rank fuels such as subbituminous coals and lignites contain relatively large amounts of moisture compared to higher rank coals. High fuel moisture results in fuel handling problems, and it affects station service power, heat rate, and stack gas emissions.

This project deals with lignite and subbituminous coal-fired pulverized coal power plants, which are cooled by evaporative cooling towers. The project involves use of the hot circulating cooling water leaving the condenser to provide heat needed to partially dry the coal before it is fed to the pulverizers.

Recently completed theoretical analyses and coal test burns performed at a lignite-fired power plant showed that by reducing the fuel moisture, it is possible to reduce water consumption by evaporative cooling towers, improve boiler performance and unit heat rate, and reduce emissions. The economic viability of the approach and the actual impact of the drying system on water consumption, unit heat rate and stack emissions will depend critically on the design and operating conditions of the drying system.

This project is evaluating alternatives for the low temperature drying of lignite and Power River Basin (PRB) coal. Laboratory drying studies are being performed to gather data and develop models on drying kinetics. In addition, analyses are being carried out to determine the relative costs and performance impacts (in terms of heat rate, cooling tower water consumption and emissions) of drying, along with the development of an optimized system design and recommended operating conditions.

Results

During the last Quarter, coal drying experiments were performed with a Powder River Basin coal to measure the effects of fluidization velocity and drying temperature on rate of drying in a batch drying process. The data show drying rate increases with air velocity and drying temperature. Comparisons to computational results using the batch bed drying model show good agreement between the experimental data and the theoretical predictions. Comparisons to drying results with North Dakota lignite at the same process conditions confirm the lignite dries more rapidly than the PRB. For the process conditions at which the comparisons were made, the differences are from 6 to 8 percent.

Experiments were also carried out to determine the effects of inlet air humidity on drying rate. The specific humidity ranged from a value typical for air at temperatures near freezing to a value for 30°C air at 90 percent relative humidity. The experimental results show drying rate is strongly affected by inlet air humidity, with the rate decreasing with more humid inlet air. The temperature of the drying process also plays

a strong role, with the negative impacts of high inlet moisture being less of a factor in a higher temperature drying process. In the case of PRB coal being dried at 43°C, drying rate decreased by 60 percent as the specific humidity went from the low to high value. At 66°C, the drying rate decreased by 30 percent over the same range of inlet air humidities. Lignite drying followed these same trends, with a 55 percent drop in drying rate at 43°C and a 20 percent decrease at 66°C.

Several concepts for coal drying systems integrated into a power plant were developed. These make use of hot circulating cooling water from the condenser, steam extraction from the turbine cycle and thermal energy extracted from hot flue gas, in various combinations. Analyses are under way to calculate the effects of drying system design and process conditions on unit performance, emissions, and cooling tower makeup water.

EXPERIMENTAL

Test Apparatus

The drying experiments are being performed in the Energy Research Center's Fluidized Bed Laboratory. The bed vessel is 152.4 mm (6") in diameter, with a 1372 mm (54") column and a sintered powder metal distributor plate. The air and entrained coal particles flow into a filter bag before the air is discharged from the apparatus (Figure 6). Compressed air used in the experiments flows through a rotameter and an air heater before entering the plenum. In some experiments, steam is injected into the air to increase its moisture content before it enters the dryer. Operating at 1.6 m/s of superficial air velocity in the 152.4 mm (6-inch) diameter bed, the electrically heated, air heater can attain a maximum steady state temperature of 66°C (150°F).

Figure 6: Sketch of Experimental Bed Setup

Thermocouples inserted through the bed wall are used to measure vertical distribution of bed temperature. A horizontal bundle of eighteen 12.7 mm ($\frac{1}{2}$ ") diameter

electric heating elements is used to provide in-bed heating. The heaters are located in the region from 51 mm (2") to 304.8 mm (12") above the distributor and are instrumented with thermocouples to indicate heater surface temperature. By controlling power to the heaters, the heater surface temperature can be operated in a range from 38°C (100°) to 65.6°C (150°F). At a given heater surface temperature, total heat flux to the bed can be reduced from the maximum by disconnecting selected heaters from the power supply.

Test Procedure

The desired amount of coal was loaded into the apparatus. The flow rate and temperature of the inlet air and the power level to the in bed heaters were set. Small samples of the coal were removed from the bed during the drying tests and coal moisture was measured. This was determined by drying samples of the coal in crucibles in an oven at 110°C for 5 to 6 hours, and weighing the samples before and after drying. The complete test procedure used in these experiments is described in Table 1.

Table 1
Procedure for Drying Tests

1. With no coal in bed, turn on compressor, set air flow to desired value, turn on air preheater and allow system to reach steady-state at desired temperature. Measure inlet relative humidity and dry bulb temperature of air.
2. Once air is at steady-state, turn off air preheater and air flow, load coal into bed, turn on all heaters and air flow to appropriate values, start stopwatch, and record pressure of inlet air from pressure gauge above rotameter.
3. Begin recording temperatures after 5 minutes, collect small samples of lignite from bed, measure wet and dry bulb temperatures at exit of bed, record values for temperature readings at each assigned thermocouple, adjust voltage regulators for the heaters so that surface temperatures remain steady at appropriate values, and repeat this procedure for each time interval on data sheet.
4. At end of test, shut off heaters but keep air flow on to cool the heaters, detach filter bag, load coal samples into crucibles, place crucibles into oven, set to 100°C, and leave for 5-6 hours or overnight, remove remaining lignite from the bed and weigh it.
5. Analyze results.

Results and Discussion

The experiments performed in this reporting period were carried out with two coals, a North Dakota lignite and a Powder River Basin (PRB) coal. The as-received moisture content of the lignite varied slightly from sample-to-sample, usually ranging from 35 to 38 percent (expressed as mass of moisture/mass of as-received fuel) and from 54 to 58 percent (expressed as mass of moisture/mass dry fuel). The PRB coal had a moisture content of approximately 27 percent (expressed as mass of moisture/mass of as-received fuel) and 37 percent (expressed as mass of moisture/mass dry fuel). All tests were carried out with coal having a minus ¼" (6350 µm) size distribution. The settled bed depth was 0.39 m.

During the first minute or two of each test, fines were elutriated from the bed. The drying rate, $\dot{\Gamma} \left(\frac{\text{kg H}_2\text{O}}{\text{kg dry coal} \times \text{min}} \right)$, presented here is based on the dry coal which remained in the bed after elutriation had occurred and after coal samples had been removed for analysis.

Drying Rates with PRB Coal

Previous progress reports contained data on drying of a lignite coal, and the effects of superficial air velocity, inlet air temperature, in bed heat flux and bed depth were shown. Figure 7 shows the effect of superficial air velocity on the drying curves for a PRB coal. These tests were run with constant inlet air and heater temperatures and inlet air specific humidity; and all of them show typical drying behavior of an initial constant slope (or initial drying rate), followed by a decreasing rate of drying. The results also show that drying rate increased with increasing superficial velocity (U_0). Figure 8 summarizes the effect of U_0 on initial drying rate, $\dot{\Gamma}$, for 43° and 66°C drying temperatures.

Figure 7: Moisture Content Versus Time – PRB Coal

Figure 8: Drying Rate Versus Velocity – PRB Coal

Figure 9 gives the relations between equilibrium coal moisture, relative humidity of air and temperature for both the lignite and PRB coals tested. These results show that the equilibrium relation does depend on coal type and this is important since the mathematical models for drying require a relation for $\Gamma = \Gamma(\phi, T)$. (See Ref. 2 and 3 for description of mathematical drying models.)

Figure 10 is a comparison between the experimental data on $\dot{\Gamma}$ and the computer predictions for PRB. These agree to within 6 percent. Also shown for reference here is the computer prediction for lignite drying for the same process conditions. Previous test results (Ref. 4) showed that lignite dries slightly more rapidly than PRB. These computer predictions are further confirmation of these relative rates.

Effect of Inlet Air Humidity on Drying Rate

A series of tests was performed with both lignite and PRB to determine the effects of inlet air moisture on the drying kinetics. With these experiments, steam was injected into the inlet air to the dryer to raise the specific humidity of the inlet air (ω_1) to values greater than those leaving the compressor. The values of ω_1 ranged from 0.004 to 0.024. The lower value of ω_1 corresponds to ambient air at temperatures near freezing. An ω_1 of 0.024 occurs at 90% relative humidity and a dry bulb temperature of 30°C.

Figure 11 shows the effect of ω_1 on the drying curves for 3 tests with PRB coal. These show clearly a reduction in drying rate with increasing ω_1 . With less evaporation occurring, the heat input to the bed results in an increase in bed temperature (Figure 12). The relative humidities of the air leaving the bed (Figure 13) show that during the latter stages of the drying process the air is closer to saturation with high ω_1 . The data in Figures 11 to 13 were obtained with a drying temperature of 43°C. Figures 14 to 16 show the corresponding results for PRB at higher inlet air temperature and in-bed heat flux.

Figure 9: Γ Versus $T\log(\phi)$ – Equilibrium Coal Moisture

Figure 10: Drying Rate Versus Velocity – PRB and Lignite

Figure 11: Coal Moisture Content Versus Time – PRB

Figure 12: Bed Temperature Versus Time – PRB

Figure 13: Relative Humidity Versus Time – PRB

Figure 14: Coal Moisture Content Versus Time – PRB

Figure 15: Bed Temperature Versus Time – PRB

Figure 16: Relative Humidity Versus Time – PRB

While the drying rates are still degraded due to high ω_1 , the effects are not quite as large. Figure 16 shows lower values of ϕ_2 , indicating the process is farther away from saturated conditions.

Figure 17 summarizes the effects of inlet specific humidity on PRB drying rates for 43 and 66°C inlet air temperatures. At 43°C, the drying rate decreased by 60 percent as the inlet air humidity went from 0.005 to 0.022 (kg H₂O/kg dry air). At 66°C, the reduction in drying rate was 31 percent over the same range of inlet humidities.

Figures 18 to 27 show lignite drying behavior with variations in inlet air humidity and drying temperature. Similarly to the PRB, lignite dries more rapidly with lower ω_1 , and the effects of inlet air moisture on drying rate are more pronounced at lower drying temperatures.

DRYING SYSTEM DESIGN AND ANALYSIS OF IMPACTS ON UNIT PERFORMANCE AND COST OF ENERGY

Tasks 4 and 5 involve the design of drying systems for 600 MW lignite and PRB coal-fired power plants, analysis of the effects of dryer operation on cooling tower makeup water, unit heat rate, auxiliary power and stack emissions, and estimation of the cost of energy as a function of reduction in coal moisture content and dryer design. The work in these two tasks is progressing in the following subtasks:

- Subtask 1: Estimate effects of firing dried coal on flow rates of combustion air and flue gas, required feed rate of coal to boiler, mill and fan power, boiler efficiency and unit heat rate.
- Subtask 2: Estimate required dryer size, flow rates of fluidizing air and amount of in-bed heat transfer as functions of drying temperature and coal product moisture.

Figure 17: Drying Rate Versus Inlet Humidity – PRB

Figure 18: Coal Moisture Content Versus Time – Lignite

Figure 19: Bed Temperature Versus Time – Lignite

Figure 20: Relative Humidity Versus Time – Lignite

Figure 21: Coal Moisture Content Versus Time – Lignite

Figure 22: Bed Temperature Versus Time – Lignite

Figure 23: Relative Humidity Versus Time – Lignite

Figure 24: Coal Moisture Content Versus Time – Lignite

Figure 25: Bed Temperature Versus Time – Lignite

Figure 26: Relative Humidity Versus Time – Lignite

Figure 27: Drying Rate Versus Inlet Humidity – Lignite

Subtask 3: Integrate dryer into boiler and turbine cycle and calculate overall impacts on heat rate, evaporative cooling tower makeup water and emissions.

Subtask 4: Size remaining components and develop drying system cost estimates.

Subtask 5: Perform calculations to select optimal drying system configuration and product coal moisture.

During this last Quarter, the effort was focused on Subtask 3. A brief description of the work done so far is given below.

Several drying system concepts are being evaluated in Subtask 3. Figure 28 shows one of these, a design concept which uses hot circulating cooling water leaving the condenser to heat the fluidizing air and provide hot water for the in-bed heat exchanger in the dryer. This results in a temperature of 38 to 43°C for both the fluidizing air entering the bed and in-bed heat exchanger tubes.

The drying rate experiments described in this and previous quarterly reports show a strong dependence of drying rate on drying temperature. As a consequence, drying processes which occur at lower temperatures will require a longer coal residence time, a larger dryer vessel, and higher flow rates of fluidizing air. One way to increase the drying temperature and improve dryer performance is to use steam extracted from the turbine cycle in a heat exchanger (SAH) to directly increase the temperature of the fluidizing air stream (Figure 28).

Other drying system concepts which are being analyzed involve use of hot flue gas and steam extraction from the turbine cycle to provide higher temperature heat sources in combination with the circulating cooling water from the condenser.

Work is in progress to evaluate the performance of these drying system options. The results will be included in the next few quarterly reports.

NOMENCLATURE

d_p	Particle Size
h_o	Settled Bed Depth
$\dot{m}_a$	Air Flow Rate
Q_{ave}	Average Heat Flux to Bed
$T_{a, in}$	Air Inlet Temperature
T_b	Bed Temperature
U_o	Superficial Air Velocity
Y	Coal Moisture (Kg H ₂ O/Kg Moist Coal)
ϕ	Relative Humidity
Γ	Coal Moisture $\left(\frac{\text{kg H}_2\text{O}}{\text{kg dry coal}} \right)$
$\dot{\Gamma}$	Drying Rate $\left(\frac{\text{kg H}_2\text{O}}{\text{kg dry coal} \times \text{time}} \right)$
ω	Specific Humidity of Air

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APPENDIX A

DEFINITION OF COAL MOISTURE

It should be noted that two different definitions of coal moisture are used in this report. The moisture content of coal, Y , obtained as part of a Proximate coal analysis, is expressed on a wet coal basis, as Kg H₂O/Kg wet coal. The moisture contents in Figures 3 and 4 rely on this definition. For purposes of theoretical predictions of coal moisture and analysis of dryer test data, it is much more convenient to express the moisture on a dry coal basis, Γ , as Kg H₂O/Kg dry coal. Figures 7 to 11, 14, 17, 21, 24 and 27 express coal moisture on a dry basis. The parameters Y and Γ are related by the following equation.

$$Y = \frac{\Gamma}{1 + \Gamma}$$

where $Y \equiv m_{\text{H}_2\text{O}} / (m_{\text{H}_2\text{O}} + m_{\text{DC}})$

$$\Gamma \equiv m_{\text{H}_2\text{O}} / m_{\text{DC}}$$

Figure A1 shows the relationship between Y and Γ .

Figure A1: Relationship Between Two Different Definitions of Coal Moisture