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

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ABSTRACT

This is the third 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. A description is given of the equipment, instrumentation and procedures being used for the fluidized bed drying experiments.

Laboratory data are presented on the effects of bed depth on drying rate. These show that drying rate decreased strongly with an increase in bed depth as the settled bed depth varied from 0.25 to 0.65 m. These tests were performed with North Dakota lignite having a 6.35 mm (1/4”) top size, constant inlet air and heater surface temperatures, constant rate of heat addition per unit initial mass of wet coal and constant superficial air velocity.

A theoretical model of the batch dryer is described. This model uses the equations for conservation of mass and energy and empirical data on the relationship between relative humidity of the air and coal moisture content at equilibrium. Outputs of the model are coal moisture content, bed temperature, and specific humidity of the outlet air as functions of time. Preliminary comparisons of the model to laboratory drying data show very good agreement.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES *(continued)*

LIST OF FIGURES *(continued)*

LIST OF TABLES

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.

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.

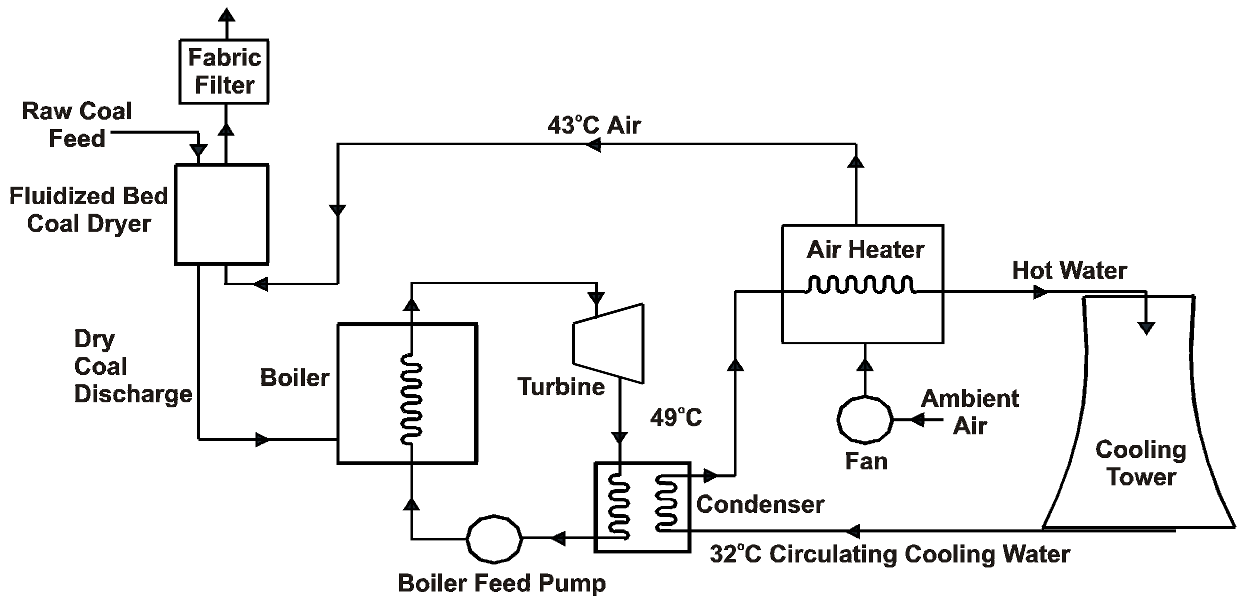

Figure 1: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 1)

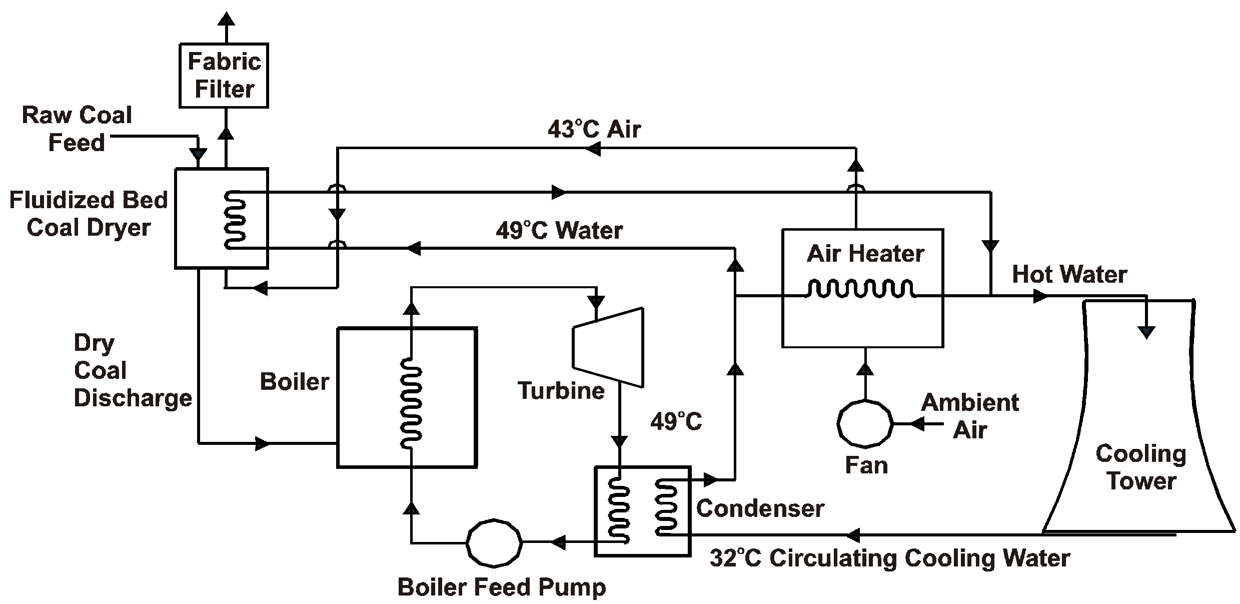

Figure 2: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 2)

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 CO_2 and SO_2 mass emissions will all be reduced by about 5 percent (Ref. 1).

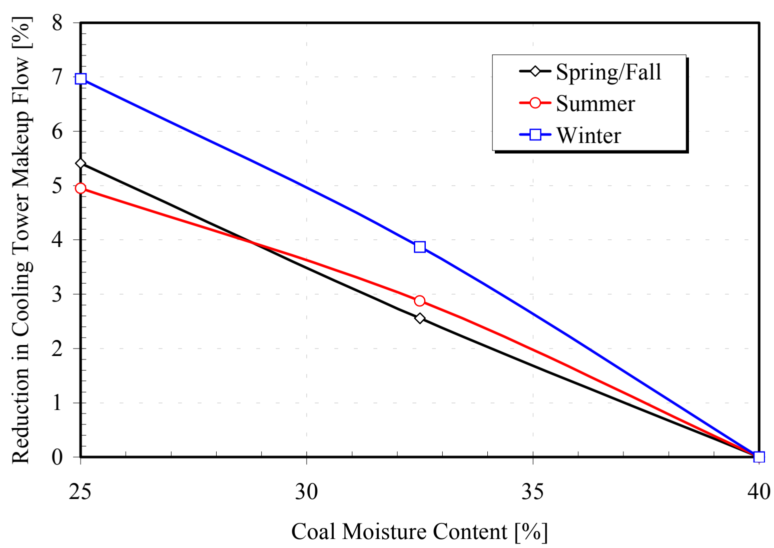

Figure 3: The Effects of Coal Moisture on Cooling Tower Makeup Water

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).

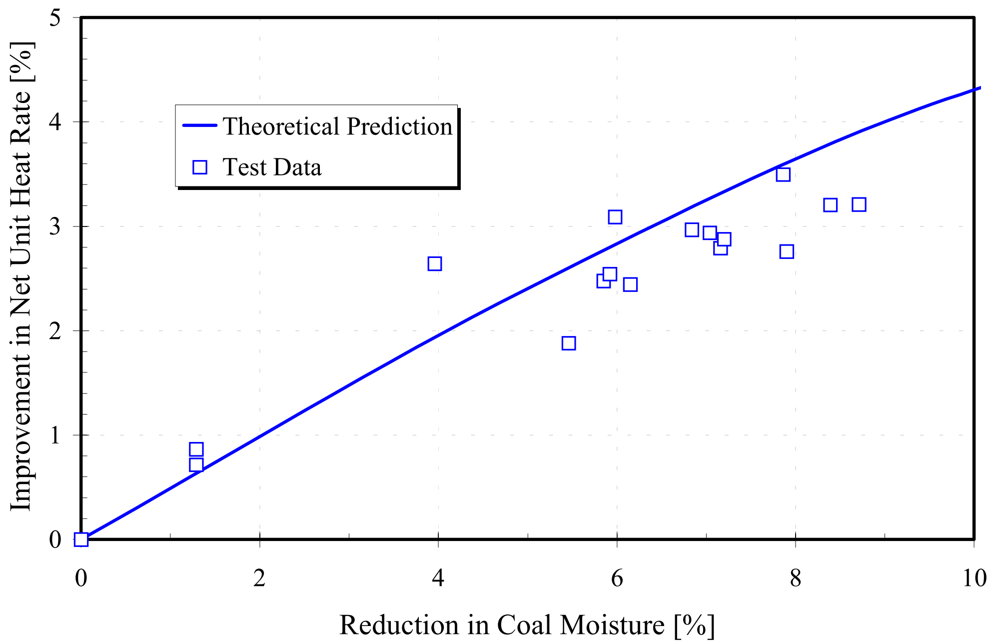

Figure 4: Improvement in Net Unit Heat Rate Versus Reduction in Coal Moisture Content

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 two alternatives (fluidized and fixed bed dryer designs) for the 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 these two drying options, along with the development of an optimized system design and recommended operating conditions.

The project is being carried out in five tasks:

Task 1: Fabricate and Instrument Equipment

Laboratory scale fixed bed and fluidized bed drying systems will be designed, fabricated and instrumented in this task.

Task 2: Perform Drying Experiments

The experiments will be carried out with both lignite and PRB coals, while varying superficial air velocity, inlet air temperature and specific humidity. In the fluid bed experiments, batch bed experiments will be run with different particle size distributions. The fixed bed experiments will include a range of coal top sizes. Bed depths will be varied for both the fixed and fluidized bed tests.

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, both fluidized bed and packed bed 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, coal particle feed size to fluidized beds and superficial air velocity for both fluidized bed and fixed bed dryers) and between dryer type.

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

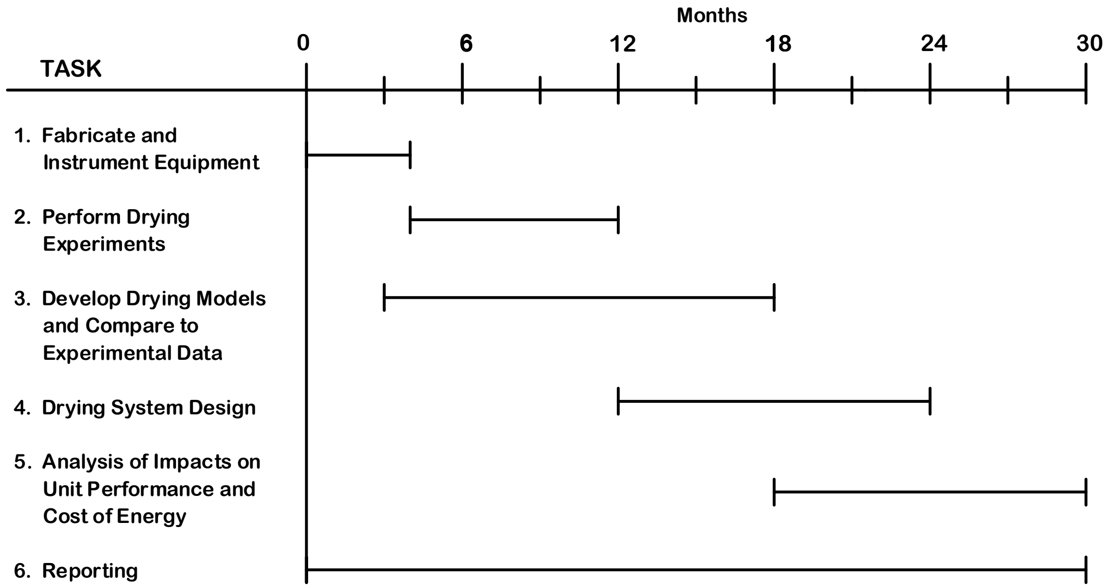

Figure 5: Project Schedule

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 the 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 two alternatives (fluidized and fixed bed dryer designs) 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

The experiments performed in this reporting period were carried out with a North Dakota lignite and examined the effects of bed depth on drying rate. The tests were performed with 6.35 mm (¼") top size coal, a 43C inlet air and heater surface temperature, relatively constant rate of heat addition per unit initial mass of wet coal (59 to 84 W/kg), and constant superficial air velocity (U_o ~ 1.14m/s). The results show that drying rate decreased with an increase in bed depth, decreasing from 0.0091 to 0.0041 kg H_2O/kg dry coal/minute as settled bed depth increased from 0.25 to 0.65 m. These data also show that as the bed depth and bed mass decreased and the moisture content of the lignite reached lower values, the exit air temperature increased and the exit specific humidity decreased more rapidly with time.

Most of the effort during the first year of the project has focused on the effects of dryer process conditions on drying rate. Having this information is key to being able to design dryers for this application, to estimate the costs of the drying system equipment and its operating costs, and to estimate the impacts of drying on cost of energy. The experiments to date show that, in addition to bed depth, drying rate is a strong function of superficial air velocity, drying temperature and heat flux from the in-bed heat exchanger to bed material. In particular, the data show that, drying rate increases with increases in fluidization velocity, drying temperature and in-bed heat flux and with reductions in bed depth.

Previous research on water in low rank coals and other porous solids, has shown that an equilibrium is established between the moisture content of the coal or porous solid and the relative humidity of the surrounding air. As the moisture content of the coal decreases, the relative humidity of the air in contact with the coal decreases. The lignite drying tests carried out under DOE Project DE-FC26-03NT41729 were performed for a range of drying conditions. The drying data, plotted as coal moisture versus outlet relative humidity show that the equilibrium data follow one curve, which within the scatter of the data, appears to apply equally well for all of the process conditions which were tested. The significance of the equilibrium drying relationship is that the relative humidity of the outlet air will be governed by the moisture content of the processed coal.

The equilibrium moisture content-relative humidity relationship, described in the previous paragraph was used, along with the equations of conservation of mass and energy, to develop a first principle model of the drying process. The resulting system of ordinary differential equations was solved by a numerical integration technique. Solutions obtained to date are in very good agreement with the measurements. Based on what has been completed so far, this model appears to be capable of accurately predicting rates of drying for a wide range of bed process conditions. Work is in progress to complete the validation and to fine-tune the model.

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 though a rotameter and an air heater before entering the plenum. 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).

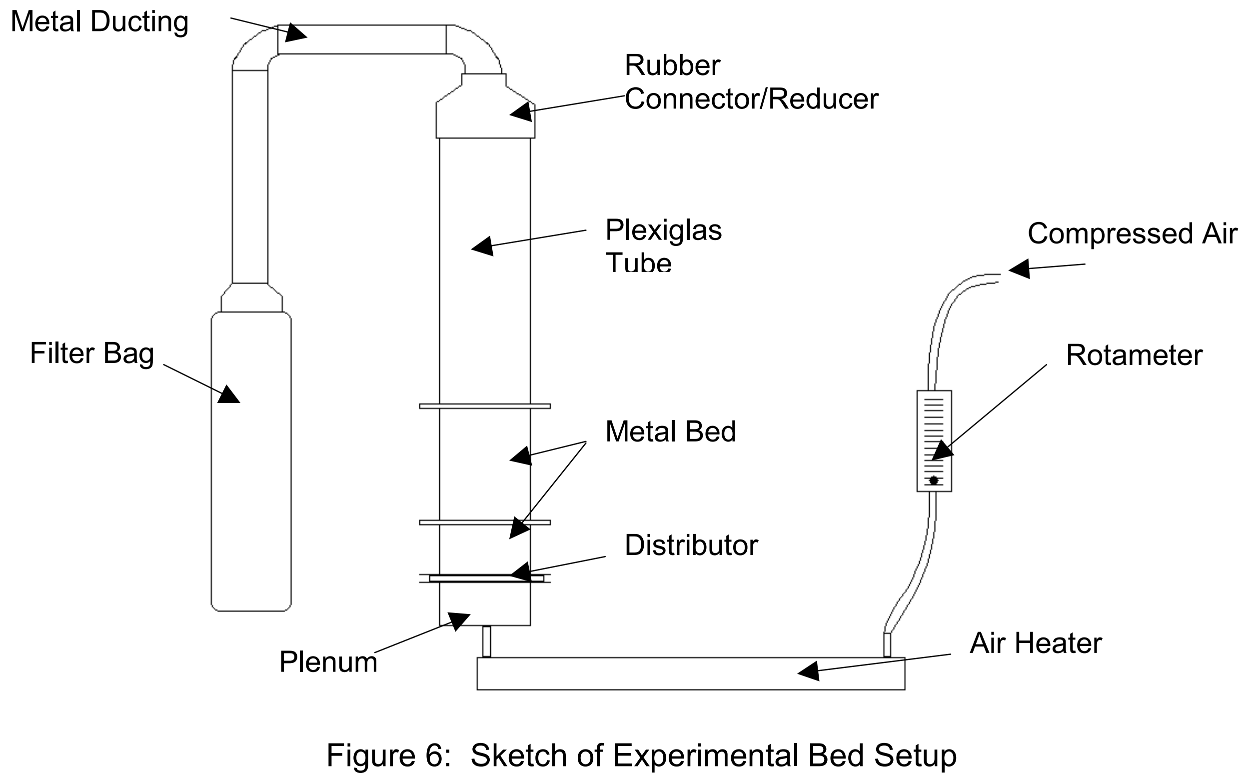

Figure 6: Sketch of Experimental Bed Setup

Thermocouples inserted through the bed wall are used to measure vertical distribution of bed temperature. A horizontal bundle of eighteen 469.9 mm (½") 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

Batch bed drying tests were performed with specific humidity of the inlet air ranging from 0.002 to 0.008. 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 North Dakota lignite provided by Great River Energy. The as received moisture content varied slightly from sample-to-sample, usually ranging from 35 to 38% (expressed as mass of moisture/mass of as-received fuel) and from 54 to 58% (expressed as mass of moisture/mass dry fuel). The experiments performed during this quarter examined the effects of bed depth on drying rate.

During the first minute or two of each test, fines were elutriated from the bed. The drying rate, $\dot{\Gamma}\left(\frac{\text{kg } H_2O}{\text{kg dry coal} \times \text{min}}\right)$, 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.

Effect of Bed Depth on Drying Rate

Experiments were performed to determine the effect of bed depth on drying rate. All of the tests were performed with 6.35 mm (¼") top size coal, a 43C inlet air and heater surface temperature, relatively constant rate of heat addition per unit initial mass of wet coal (59 to 84 W/kg), and constant superficial air velocity (U_o ~ 1.14m/s). Settled bed depth was varied from 0.25 to 0.64 m. Figure 7 shows the drying curves (Γ versus time) for the various bed depths, while Figure 8 gives the relationship between the two different definitions of coal moisture, Γ (kg H_2O/kg dry coal) and y (kg H_2O/kg wet coal). The slopes of the curves in Figure 7 are the drying rates. Numerical values for drying rates were obtained by fitting a straight line to the drying data over the first 30 minutes of each test. The drying rate results, tabulated in Table 2 and plotted in Figure 9, show that drying rate decreased with an increase in bed depth, decreasing from 0.0091 to 0.0041 kg H_2O/kg dry coal/minute as settled bed depth increased from 0.25 to 0.65 m.

The temperature and specific humidity of the inlet air were 43C and 0.004 to 0.006. Figure 10 shows the temperature of the exit air as a function of time for the various bed depths and Figure 11 shows specific humidity. The relative humidity of the exit air during the initial stage of drying is shown in Figure 12. These results show that as the bed depth and bed mass decreased and the moisture content of the lignite reached lower values, the exit air temperature increased and the exit specific humidity decreased more rapidly with time. Since exit air temperature is almost equal to bed temperature (Figure 13), this also indicates that as the bed depth (bed mass) decreased, the bed temperature increased more rapidly. Relative humidity, during the initial stage of drying, increased slightly with bed depth, ranging from 92 to 94 percent.

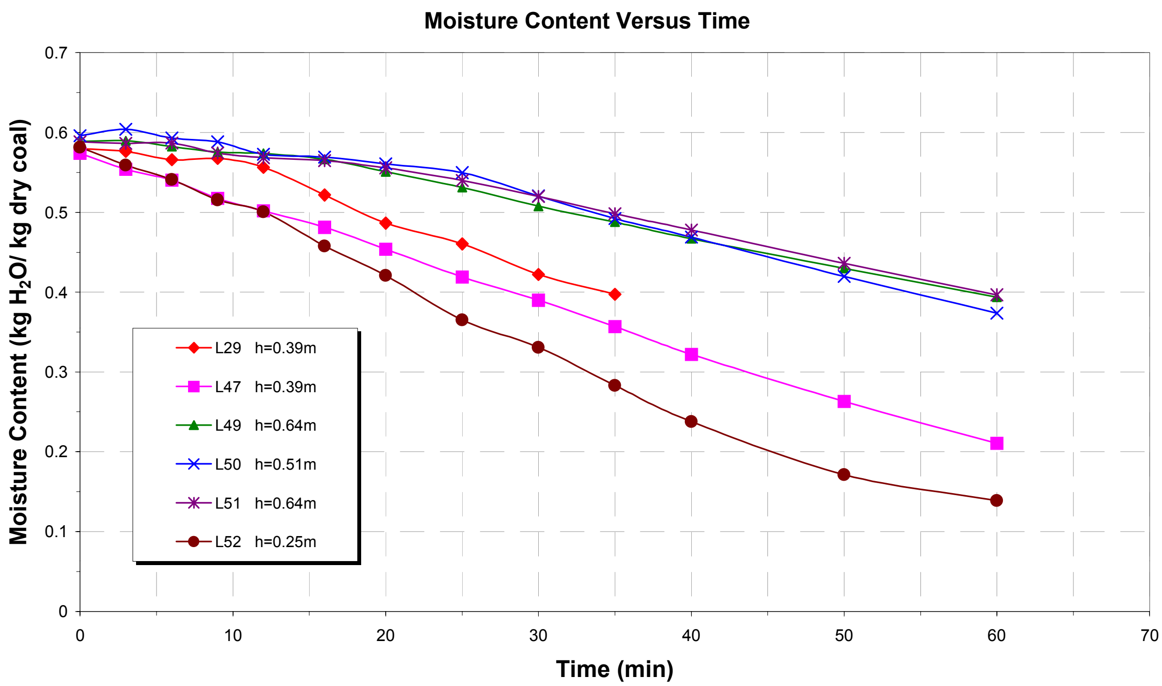

Figure 7: Drying Curves for Different Bed Depths

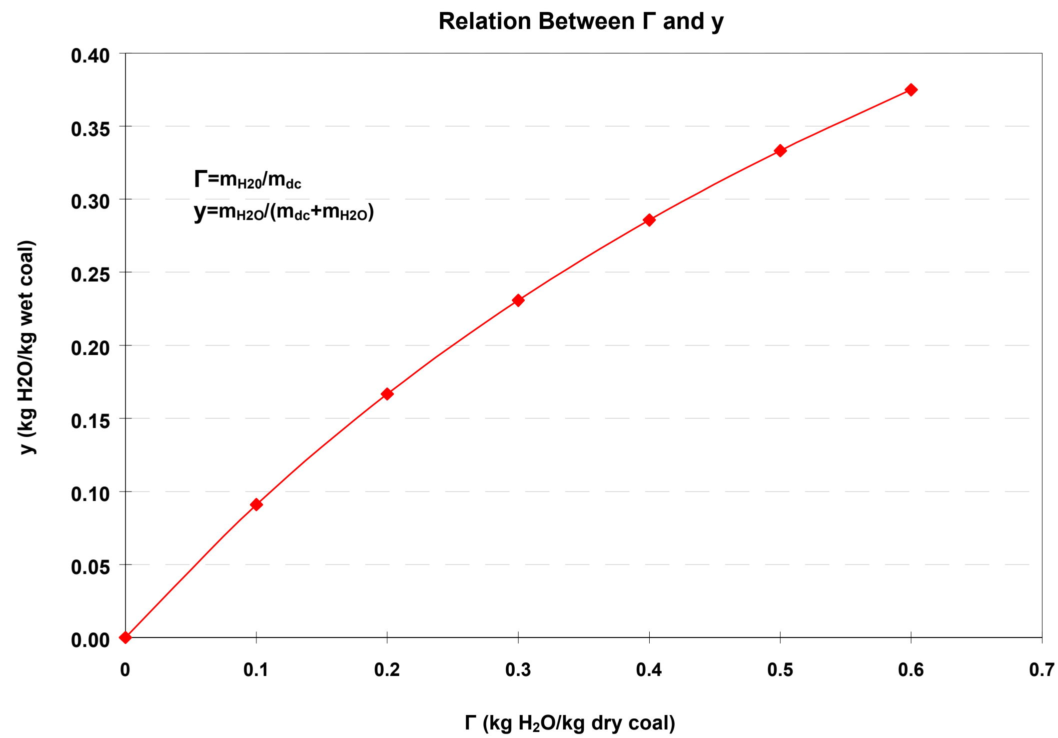

Figure 8: Relationship Between Γ and y

Table 2

Bed Depth Tests

TEST	U_o (m/s)	h_o (m)	T (°C)	$\dot{Q}/m_{wet\ i}$	$\dot{\Gamma}(1/min)$
29	1.02	0.39	43	63	0.0060
47	1.14	0.39	43	67	0.0062
49	1.14	0.64	43	59	0.0041
50	1.14	0.51	43	59	0.0048
51	1.14	0.64	43	60	0.0041
52	1.14	0.25	43	84	0.0091

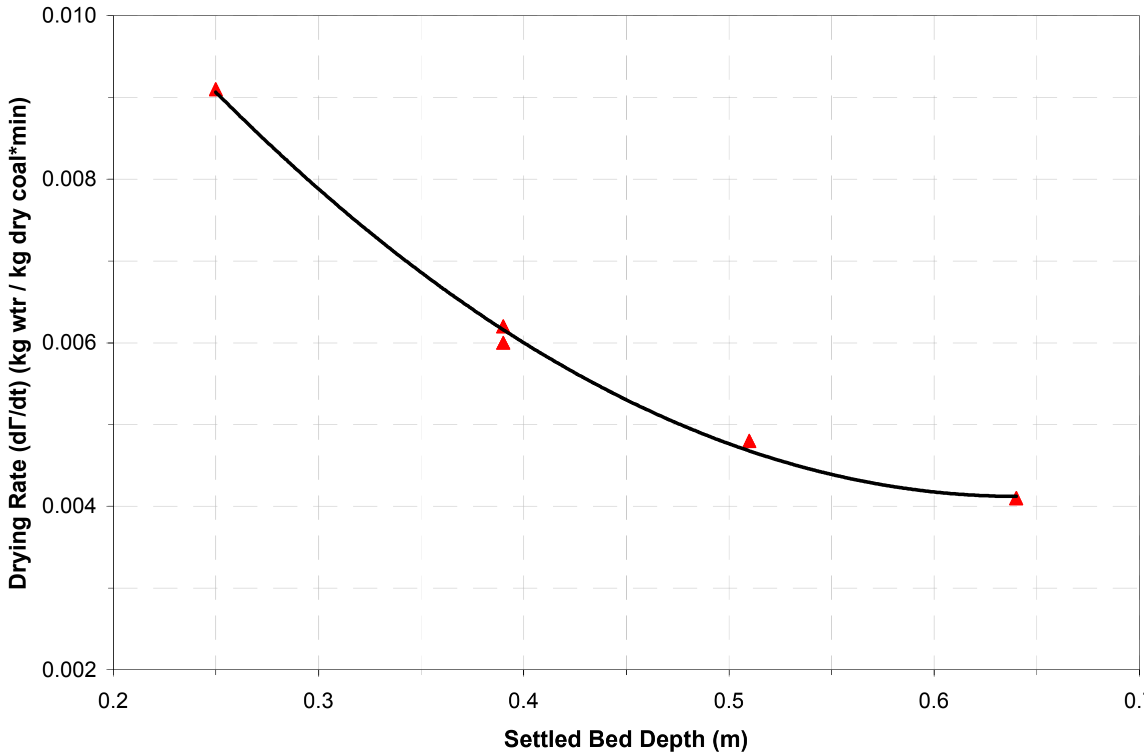

Figure 9: Drying Rate Versus Bed Depth

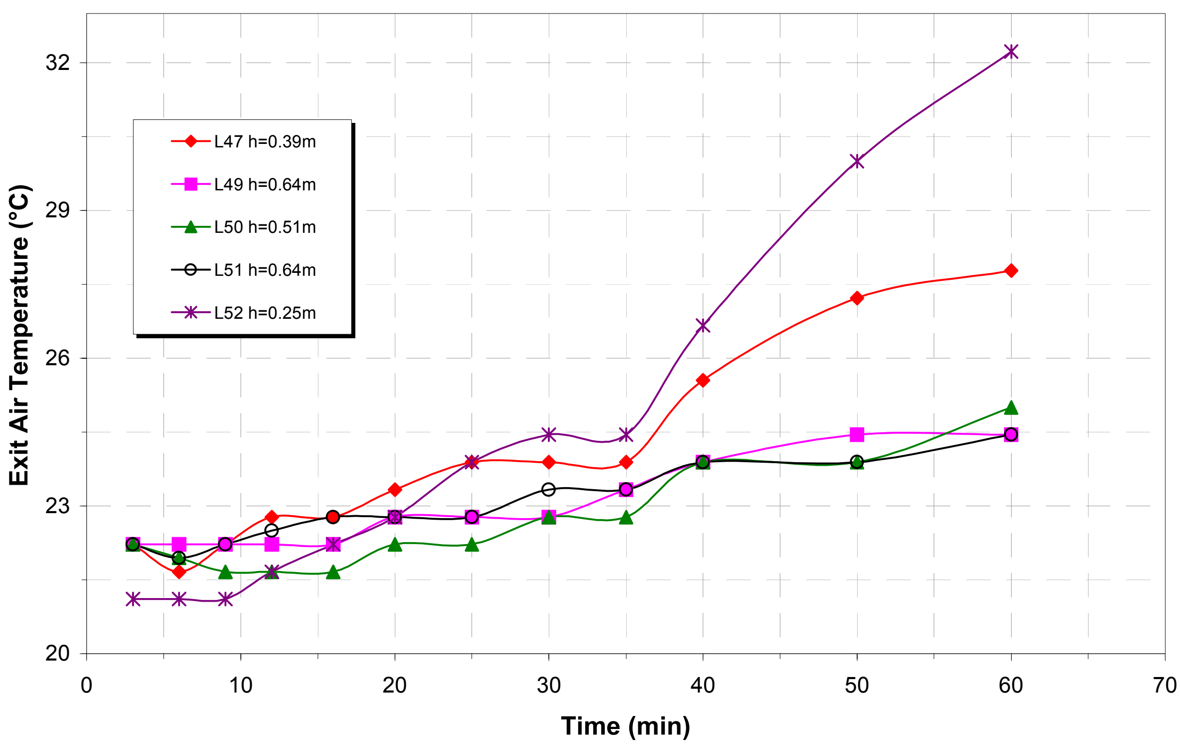

Figure 10: Exit Temperature Versus Time

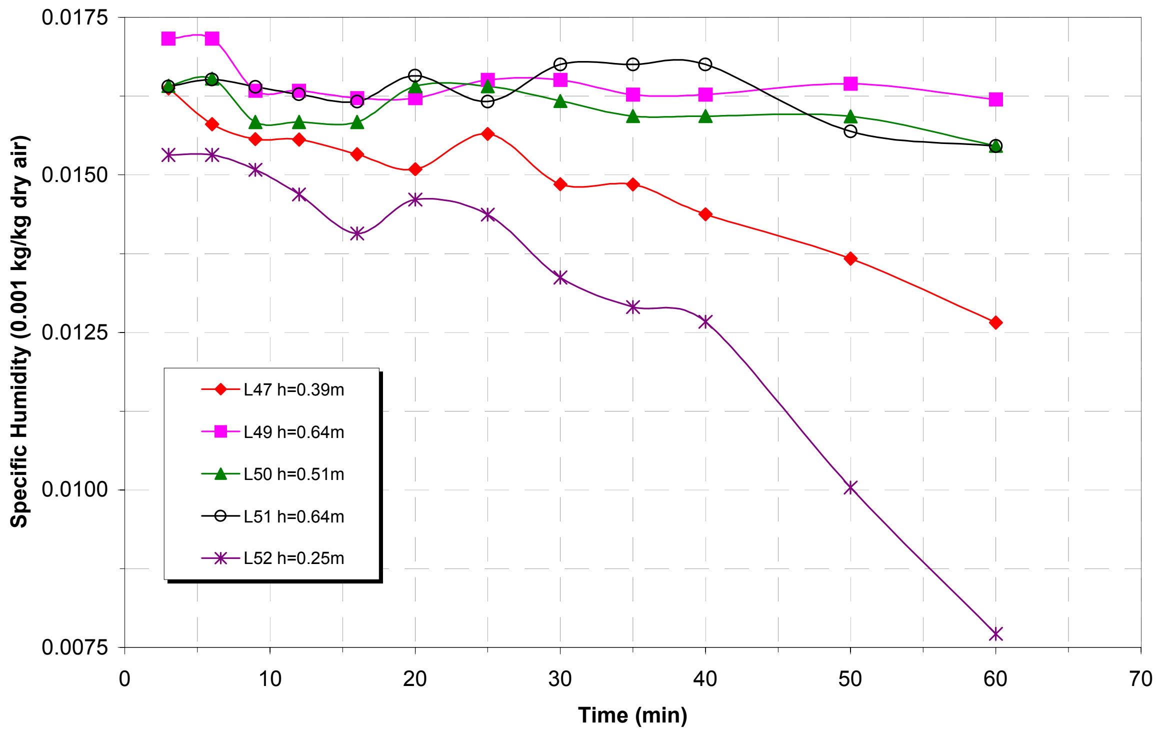

Figure 11: Outlet Specific Humidity Versus Time

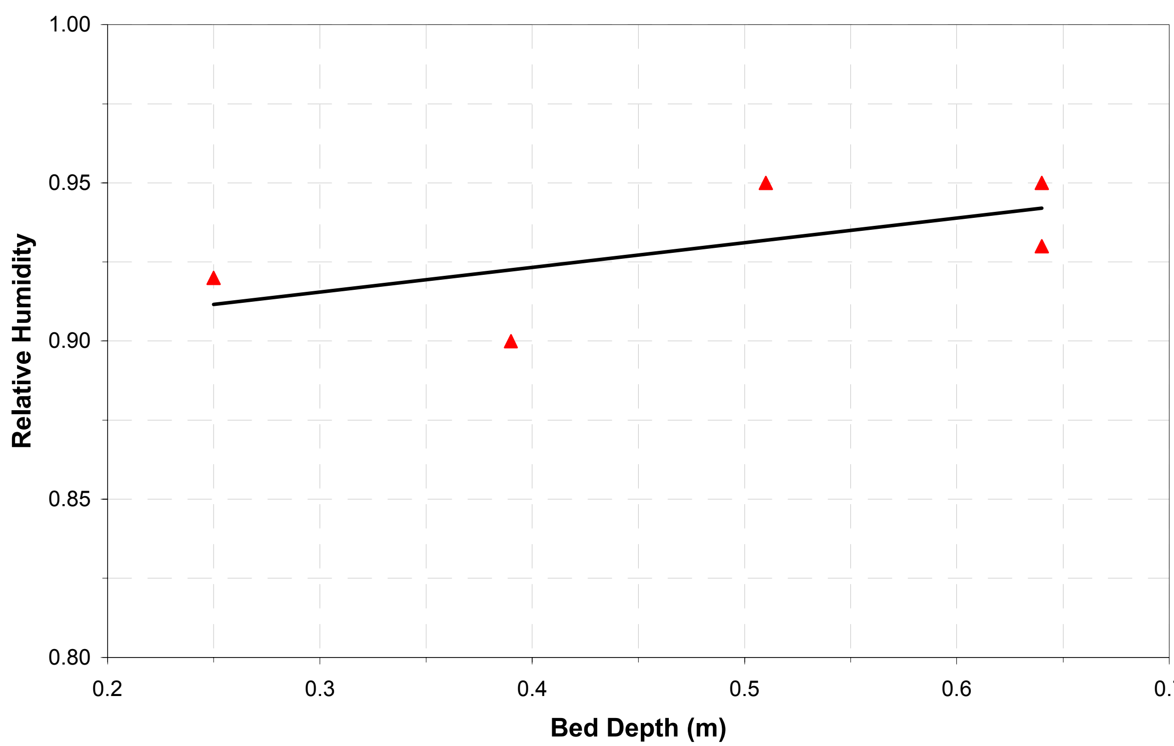

Figure 12: Relative Humidity of Exit Air Versus Bed Depth During Initial Stage of Drying

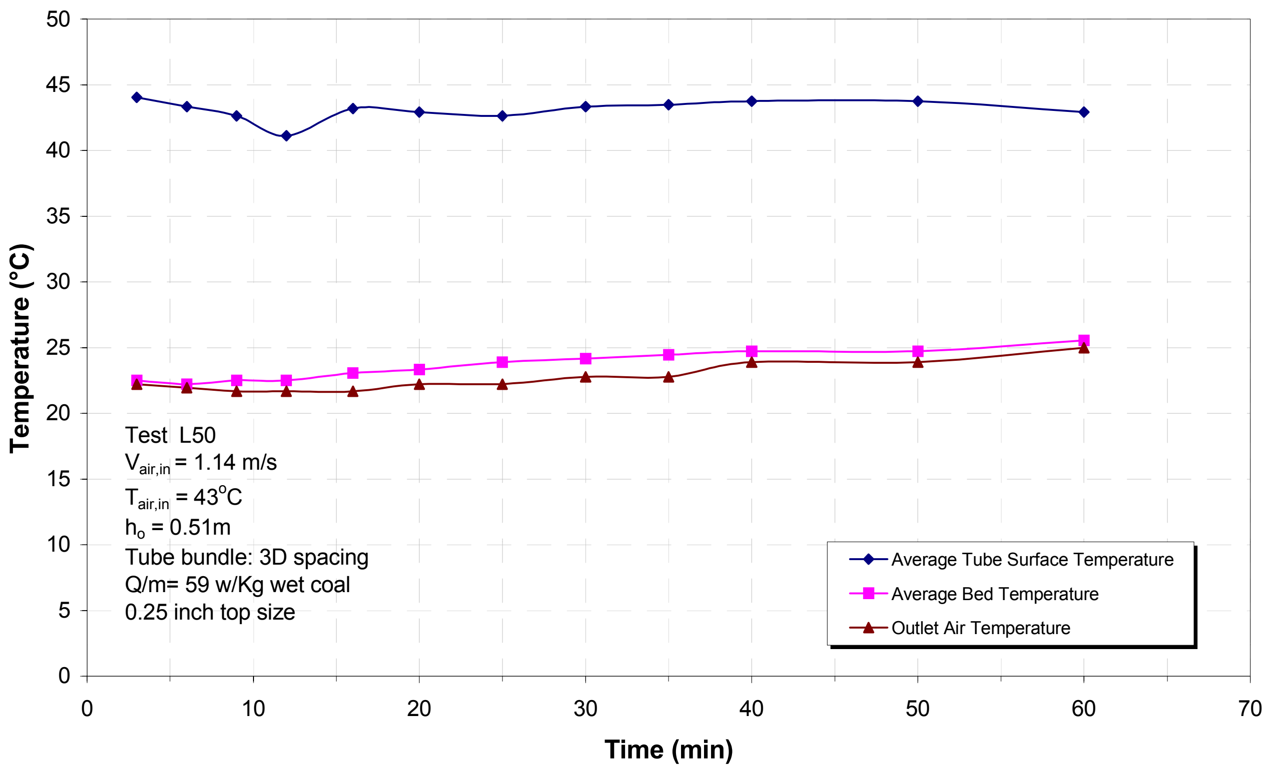

Figure 13: Average Tube Surface, Exit Air and Bed Temperatures Versus Time

These tests were performed at a fixed value of air velocity. Attempts to operate at lower velocities with deep beds resulted in poor vertical solids mixing, most likely resulting in settling of larger particles towards the distributor. We were also prevented from operating at higher velocities with deeper beds because of the onset of bed slugging.

(Note: Bed slugging occurs when the bubble size is of the same magnitude as the diameter of the bed vessel. Bubble size increases with air velocity and bed depth). The bed was 6-inch diameter in these experiments. Slugging will not be a problem in a large-scale industrial dryer, so it should be possible to operate at higher air velocities in that case, if desired.

FIRST PRINCIPLE DRYING MODEL

Relative Humidity of Air Leaving Lignite Dryer

Previous research on water in low rank coals and other porous solids, has shown that an equilibrium is established between the moisture content of the coal or porous solid and the relative humidity of the surrounding air. As the moisture content of the coal decreases, the relative humidity of the air in contact with the coal decreases (Figure 14). This relationship has a sigmoid shape, and the general relationship has been shown to apply to a wide range of coal ranks, including brown coals and bituminous coals. The sigmoid isotherm shape is also typical of physical adsorption of condensable vapors on porous adsorbents. (Refs. 2, 3)

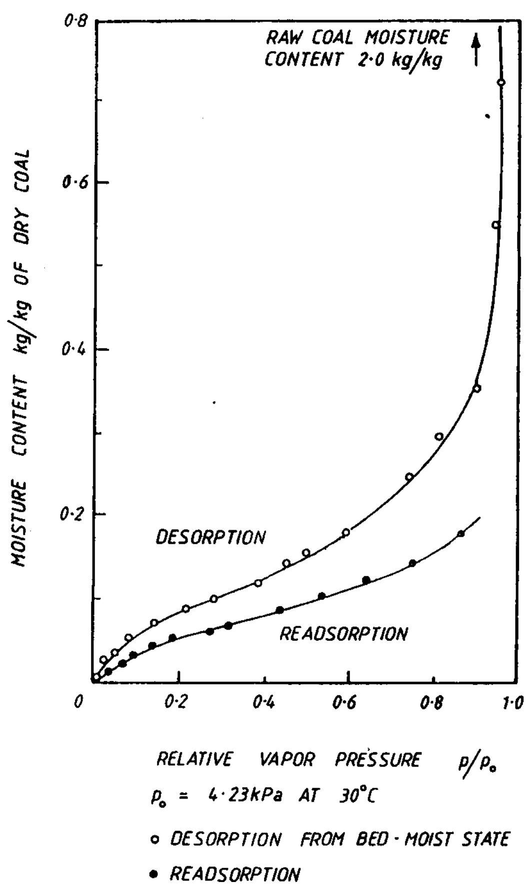

Figure 14: Water Sorption Isotherms on Yallourn Brown Coal at 30°C. (Fig. 3.2 in Ref. 2)

Previous research on brown coal from Australia has shown that above a relative humidity, $\phi = 0.96$, the water is free or bulk water admixed with the coal and contained in macropores and interstices. From $\phi = 0.5$ to 0.96, the water is desorbed from capillaries and the depression in vapor pressure can be explained by the capillary meniscus effect. Below $\phi = 0.5$, the pore sizes are predicted to be of the order of a few molecular diameters. In this region, desorption is attributed to the loss of water sorbed from multilayers on the walls of the pores. Monolayer sorption occurs below $\phi = 0.1$ (Ref. 2).

The lignite drying tests carried out under DOE Project DE-FC26-03NT41729 were performed for a range of drying temperatures, bed depths, fluidization velocities, and particle size distributions. The drying data for one set of process conditions are plotted as coal moisture, Γ, versus outlet relative humidity, ϕ, in Figure 15. This is similar to the sigmoid shape illustrated in Figure 14. Figures 16 to 18 are composite plots of replicate drying tests, with each graph containing either two or three data sets for fixed drying conditions. Figures 16 to 18 can be used to indicate the magnitude of the scatter (standard deviation) in ϕ obtained in these tests. Finally, Figure 19 shows equilibrium data for all the drying tests performed to date in this study. The standard deviation in ϕ for the complete data set is approximately the same as the standard deviation in ϕ for fixed process conditions. This indicates that the equilibrium data follow one curve, which within the scatter of the data, appears to apply equally well for all of the process conditions which were tested. We anticipate that equilibrium data for other coals will follow other curves. The functional relationship will have to be established separately for each coal of interest.

The significance of the equilibrium drying relationship is that the relative humidity of the outlet air will be governed by the moisture content of the processed coal. For example, if the lignite enters at $\Gamma = 58\%$ and is dried to $\Gamma = 30\%$, the fluidizing air will range in relative humidity from close to 95% at the inlet end of the dryer to ~70% at the discharge end.

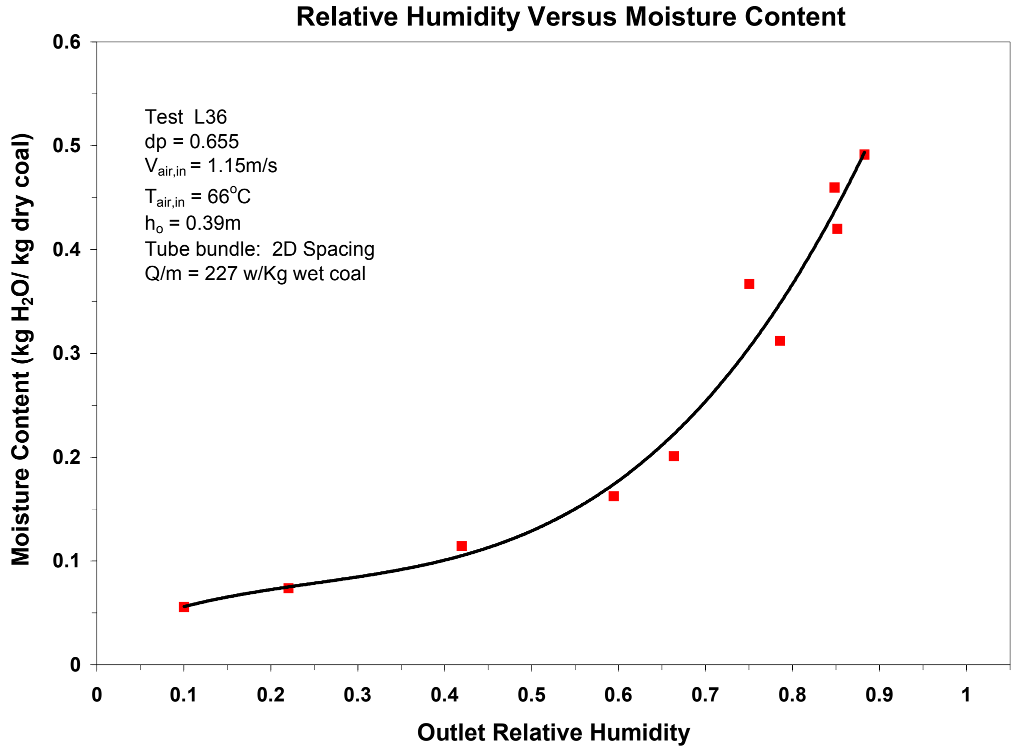

Figure 15: Relative Humidity Versus Moisture Content for One Test

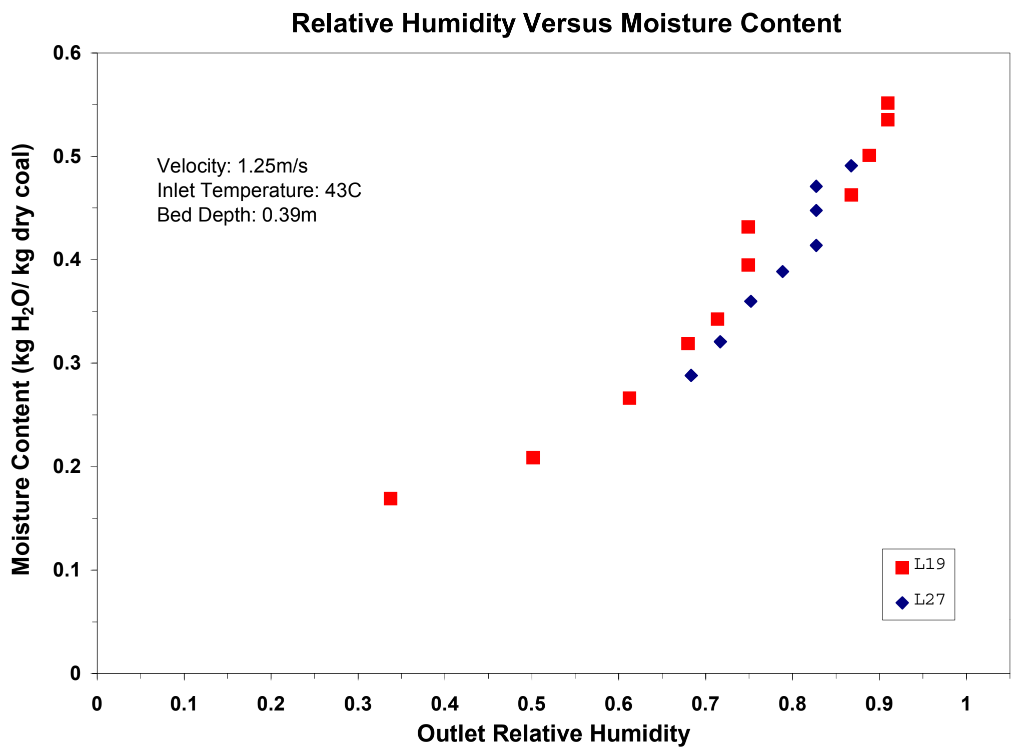

Figure 16: Data Scatter in Relative Humidity Versus Moisture Content for Two Replicate Tests

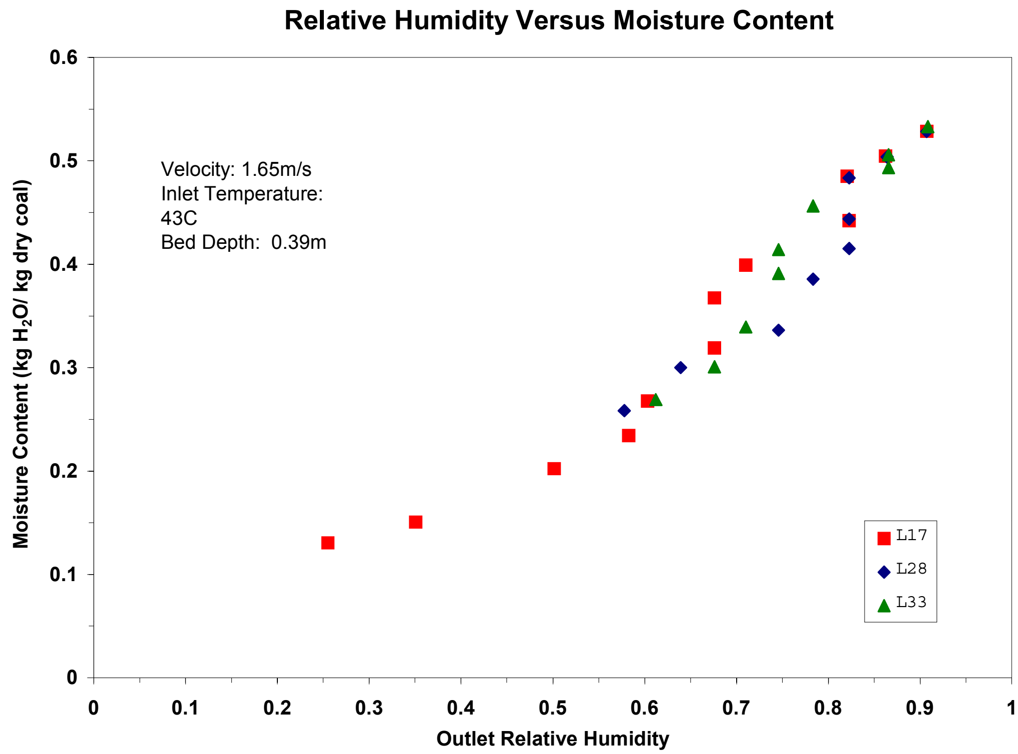

Figure 17: Data Scatter in Relative Humidity Versus Moisture Content Curve for Three Replicate Tests

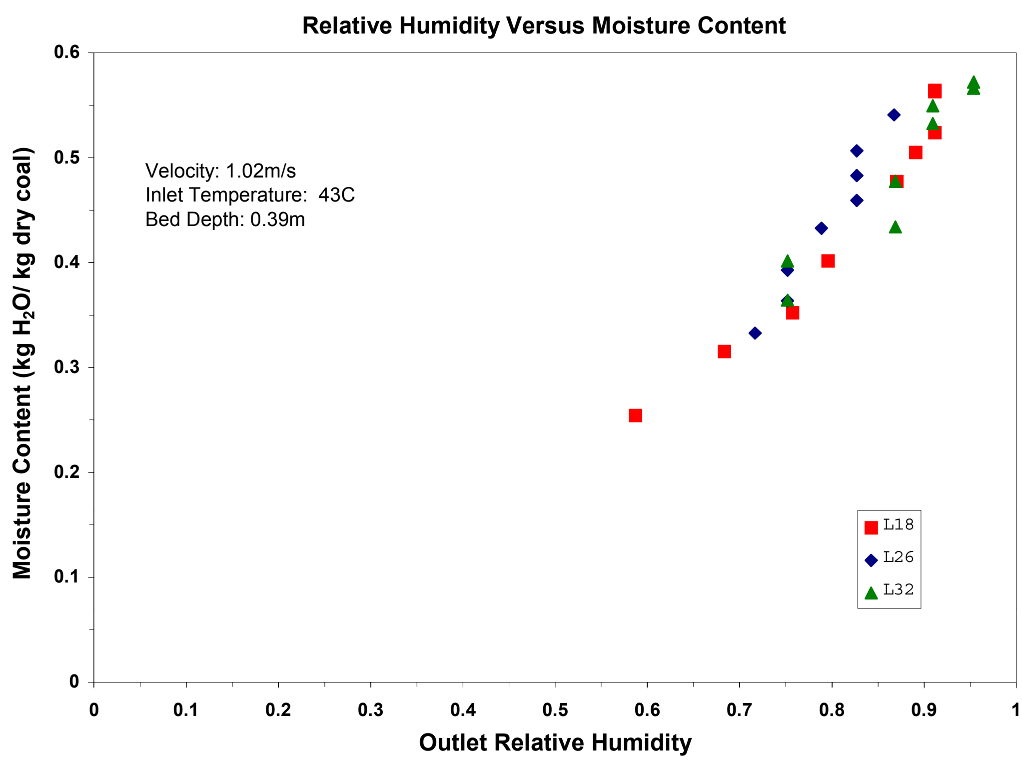

Figure 18: Data Scatter in Relative Humidity Versus Moisture Content Curve for Three Replicate Tests

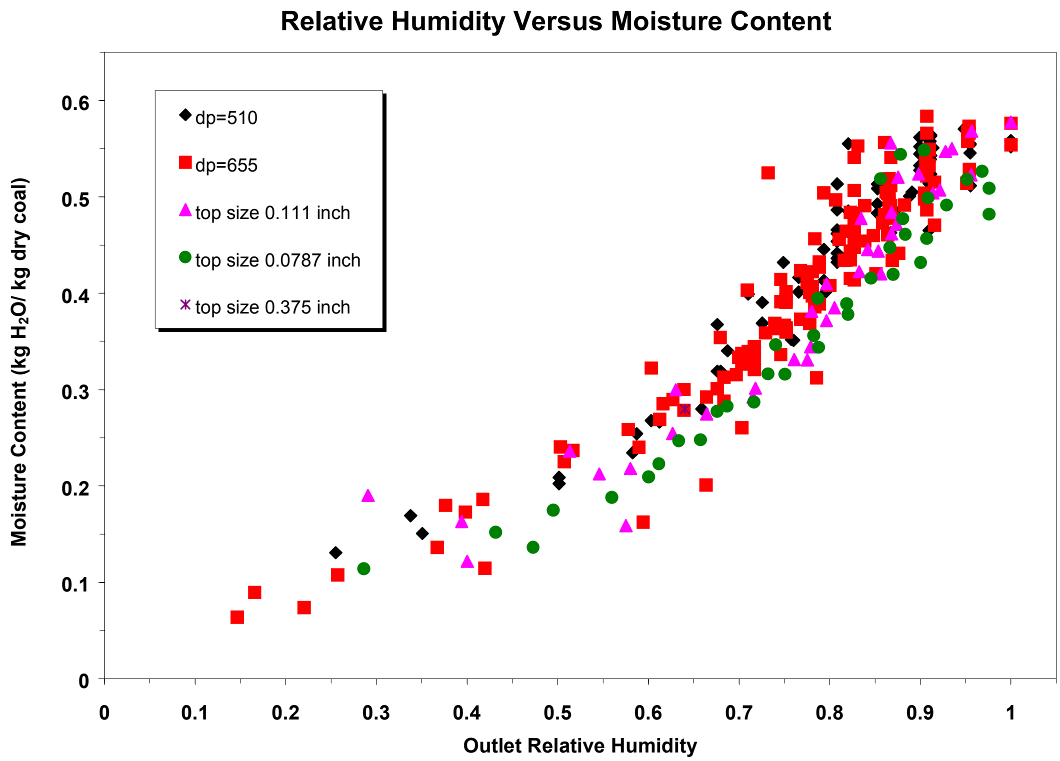

Figure 19: Relative Humidity Versus Moisture Content for Wide Range of Test Conditions

Batch Bed Drying Model

The equilibrium moisture content-relative humidity relationship, described in Figure 19 was used, along with the equations of conservation of mass and energy, to develop a first principle model of the drying process. For the batch bed, drying process illustrated in Figure 20, conservation of mass and energy can be written:

$$\frac{d\Gamma}{dt} = -\frac{\dot{m}_a}{m_{DC}}(\omega_2 - \omega_i) \quad \text{Eq. 1}$$

$$\dot{Q}_{TUBES} - \dot{Q}_{LOSS} = m_{DC}\left[(C_C + \Gamma C_L)\frac{dT_2}{dt} + u_L\left(-\frac{\dot{m}_a}{m_{DC}}\right)(\omega_2 - \omega_1)\right] + \dot{m}_a\left[C_{pa}(T_2 - T_1) + \omega_2 hg_2 - \omega_1 hg_1\right] \quad \text{Eq. 2}$$

Specific humidity, ω, can be related to relative humidity φ and air temperature T,

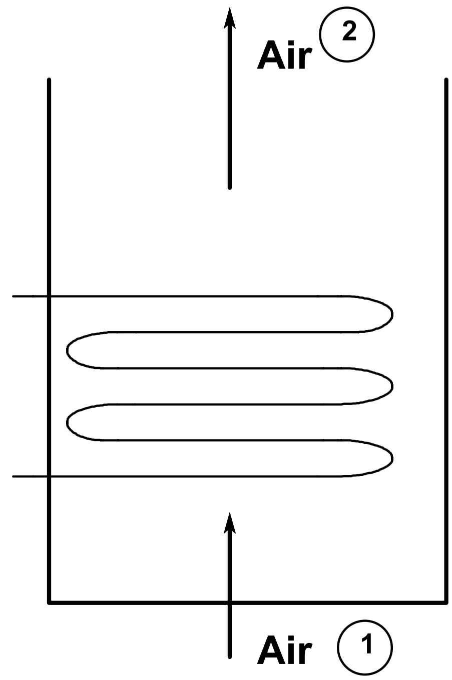

Figure 20: Sketch of Dryer Model

$$\omega = \frac{0.622\,\phi\,P_{sat}(T)}{P - \phi\,P_{sat}(T)} \qquad \text{Eq. 3}$$

while the relative humidity is an empirical function of coal moisture Γ (Figure 19).

In addition, the tube bundle heat transfer rate is

$$\dot{Q}_{TUBE} = UA(T_{TUBE} - T_{BED}) \qquad \text{Eq. 4}$$

and the parameters P_{sat} and hg are functions of air temperature.

Equations 1 to 4 form a system of ordinary differential equations for Γ and T_2 as functions of t. This was treated as an initial value problem and solved by a Runge Kutta numerical integration scheme.

Figures 21 to 32 show solutions for coal moisture content and exit air temperature, specific humidity and relative humidity as functions of time for three different sets of bed process conditions. Comparisons of the predictions with experimental data are also given in these figures.

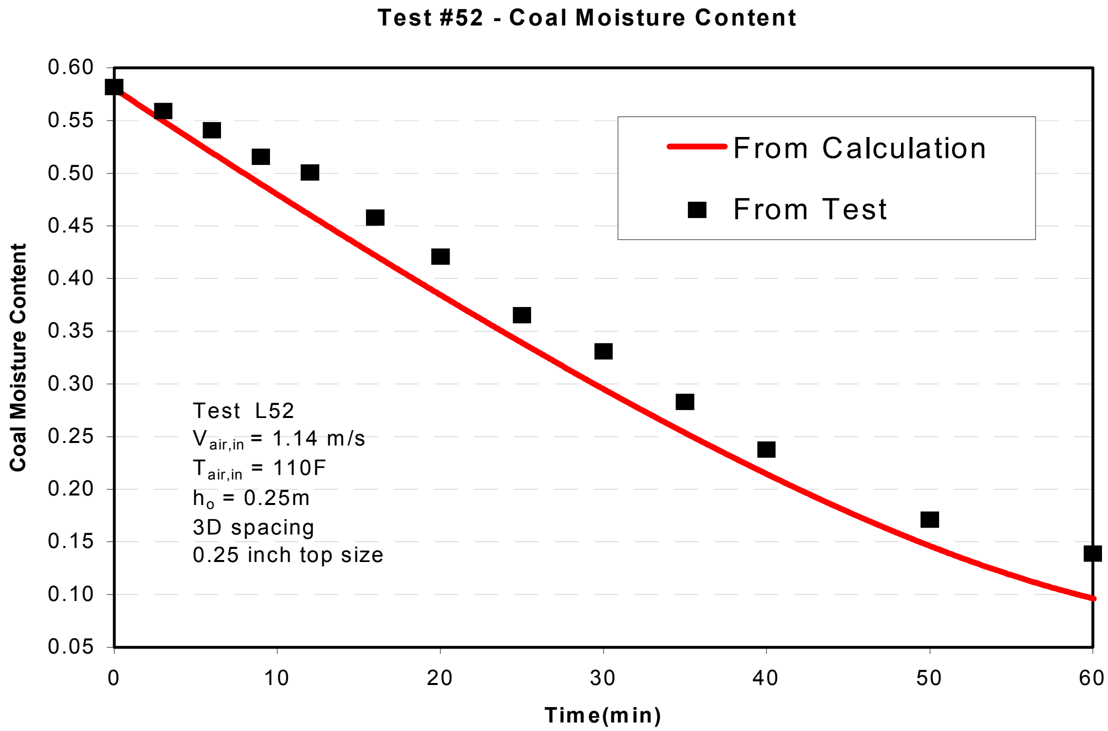

Figure 21: Coal Moisture Content Versus Time for Test 52. Comparison of Theory and Experiment.

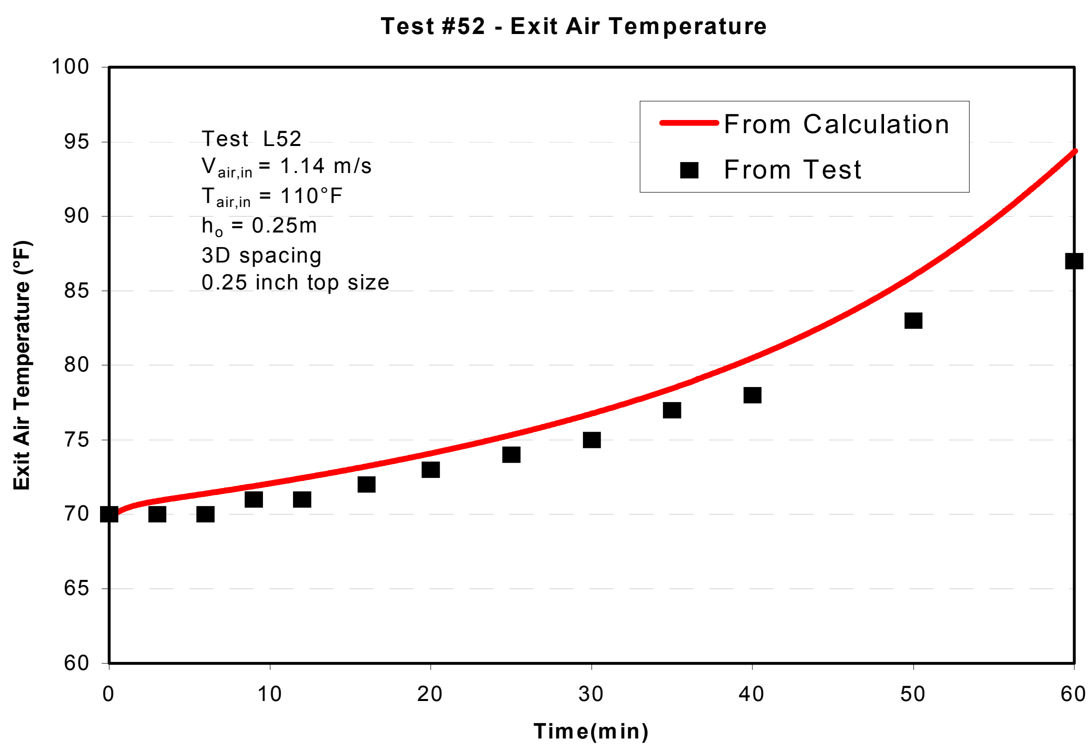

Figure 22: Exit Air Temperature Versus Time for Test 52. Comparison of Theory and Experiment.

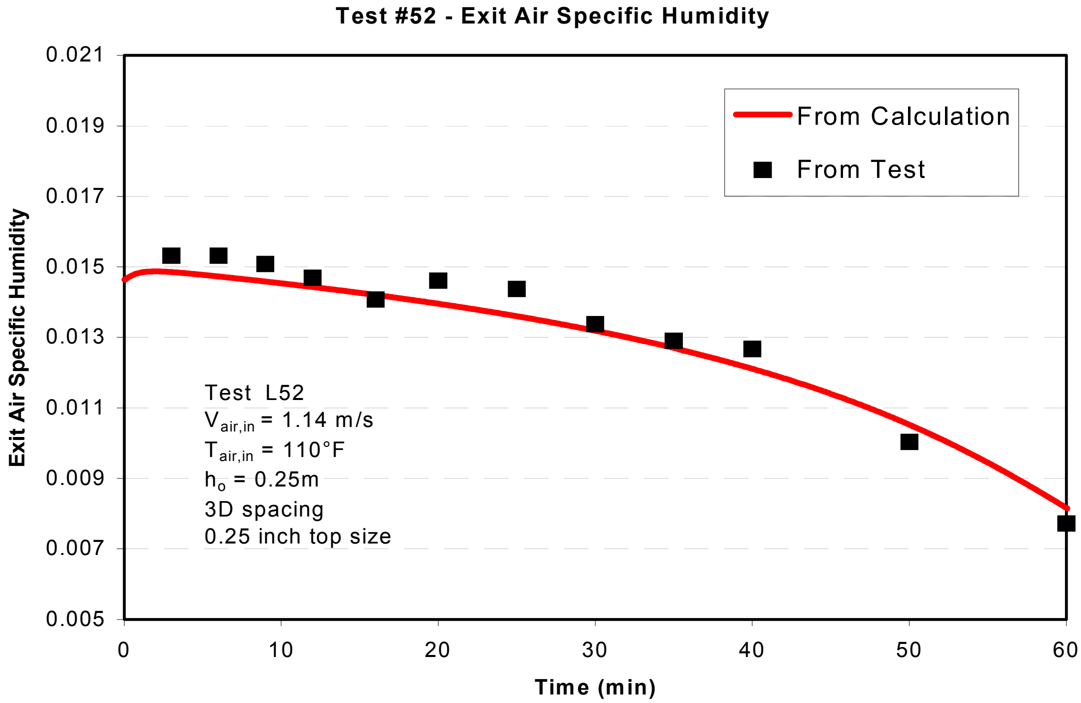

Figure 23: Exit Air Specific Humidity Versus Time for Test 52. Comparison of Theory and Experiment.

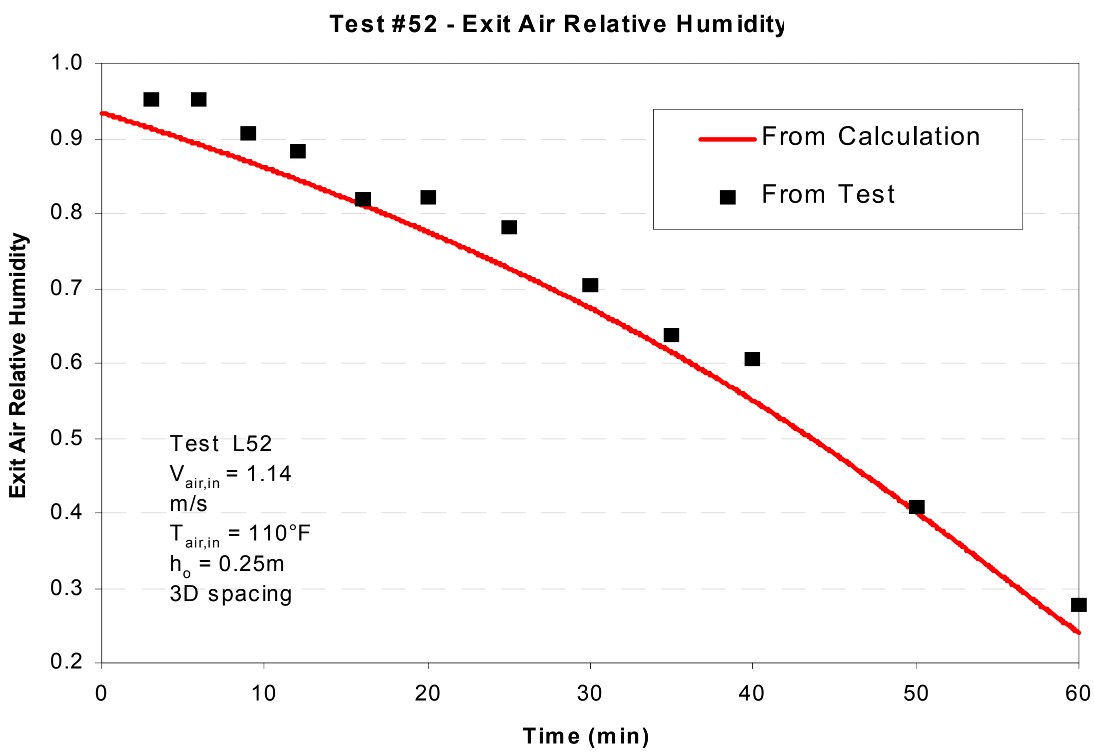

Figure 24: Exit Air Relative Humidity Versus Time for Test 52. Comparison of Theory and Experiment.

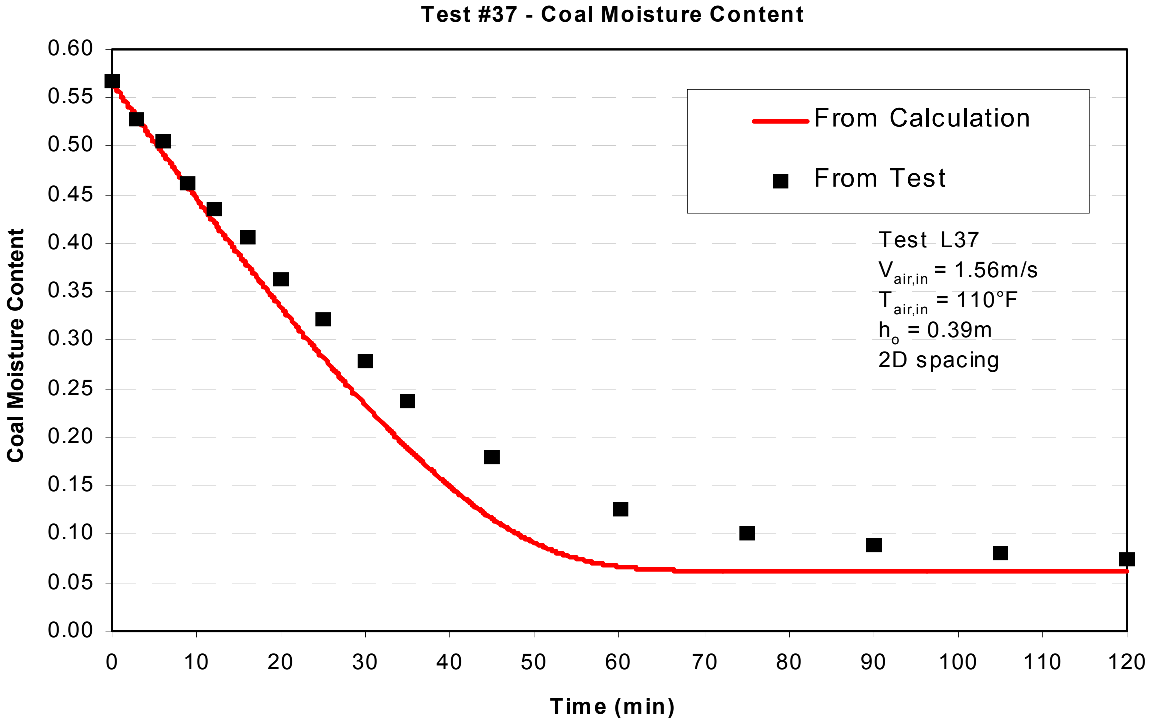

Figure 25: Coal Moisture Content Versus Time for Test 37.
Comparison of Theory and Experiment.

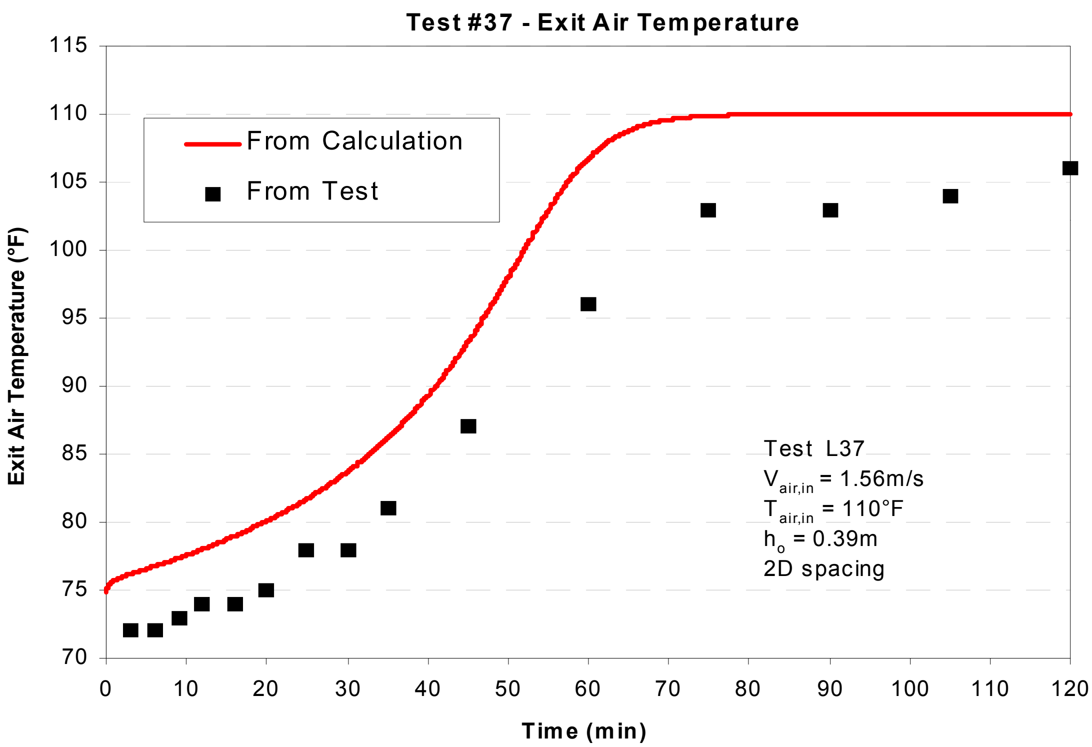

Figure 26: Exit Air Temperature Versus Time for Test 37.
Comparison of Theory and Experiment.

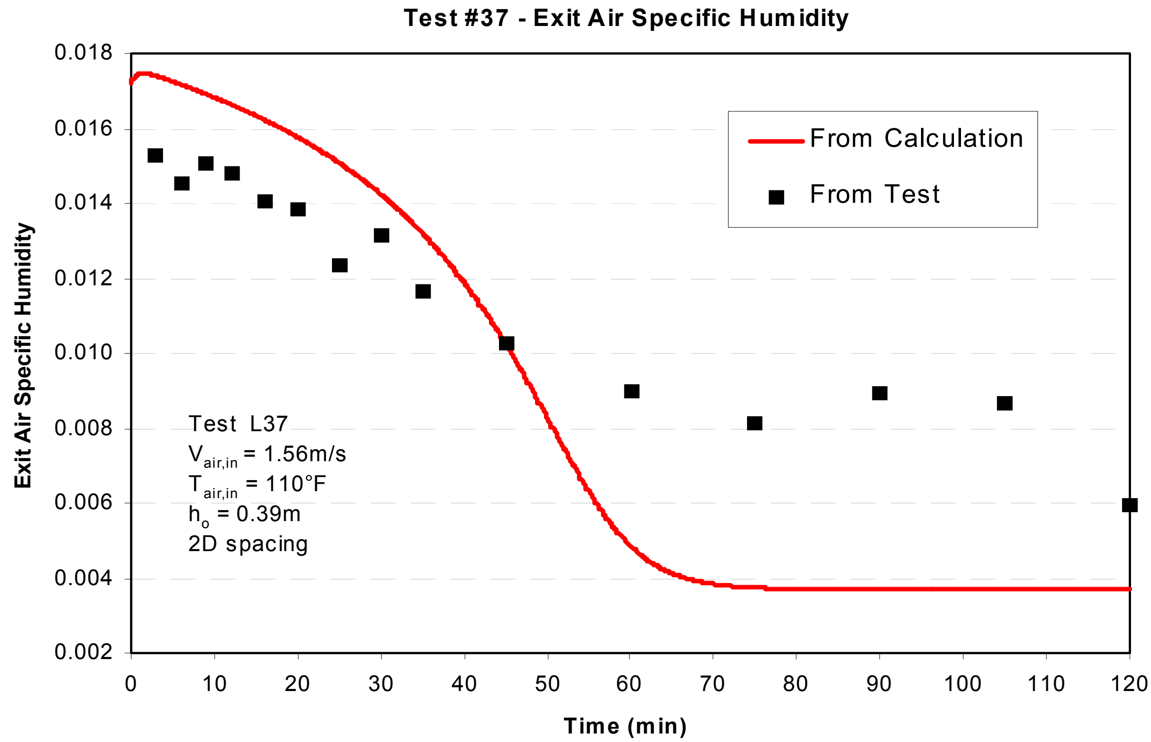

Figure 27: Exit Air Specific Humidity Versus Time for Test 37. Comparison of Theory and Experiment.

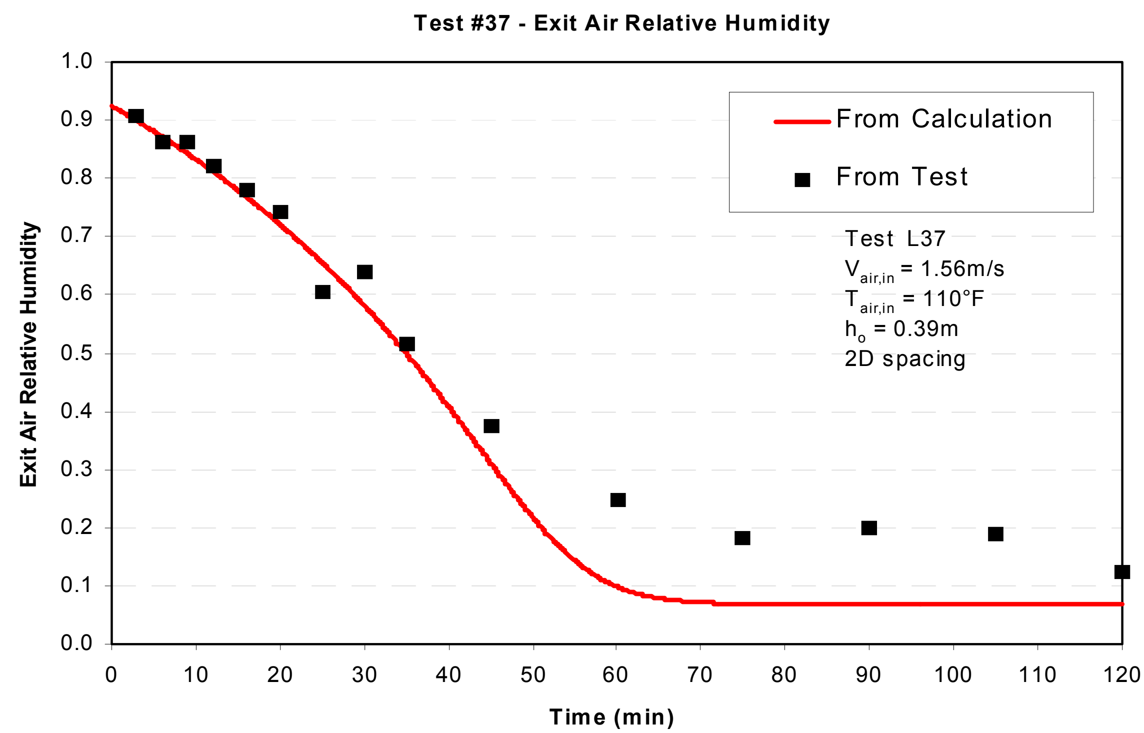

Figure 28: Exit Air Relative Humidity Versus Time for Test 37. Comparison of Theory and Experiment.

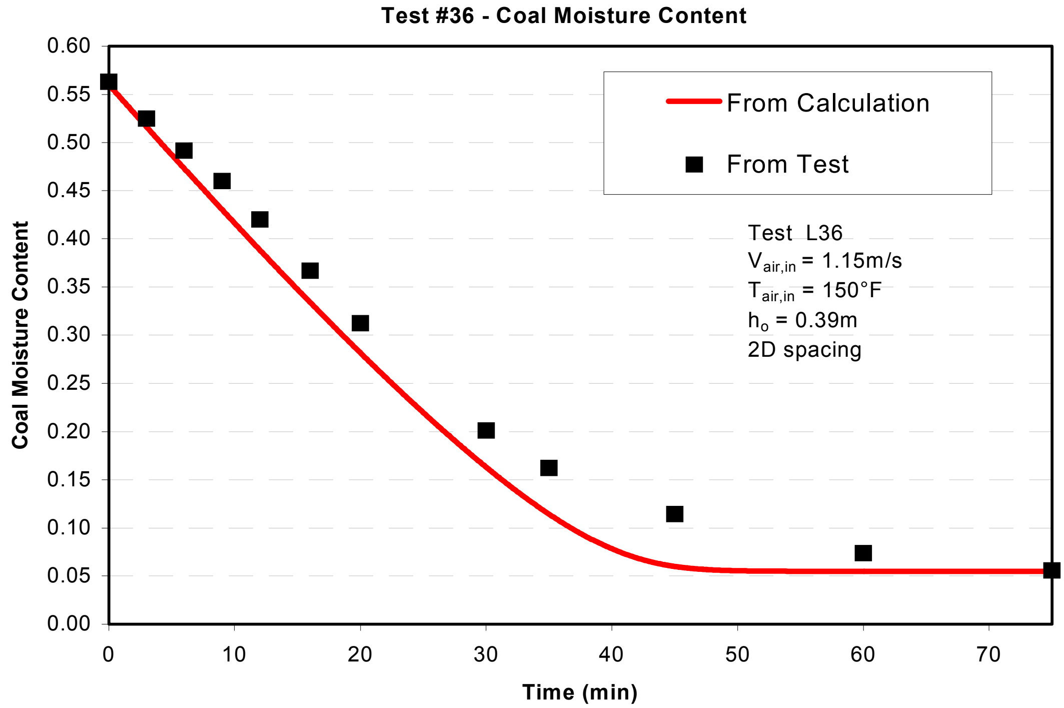

Figure 29: Coal Moisture Content Versus Time for Test 36. Comparison of Theory and Experiment.

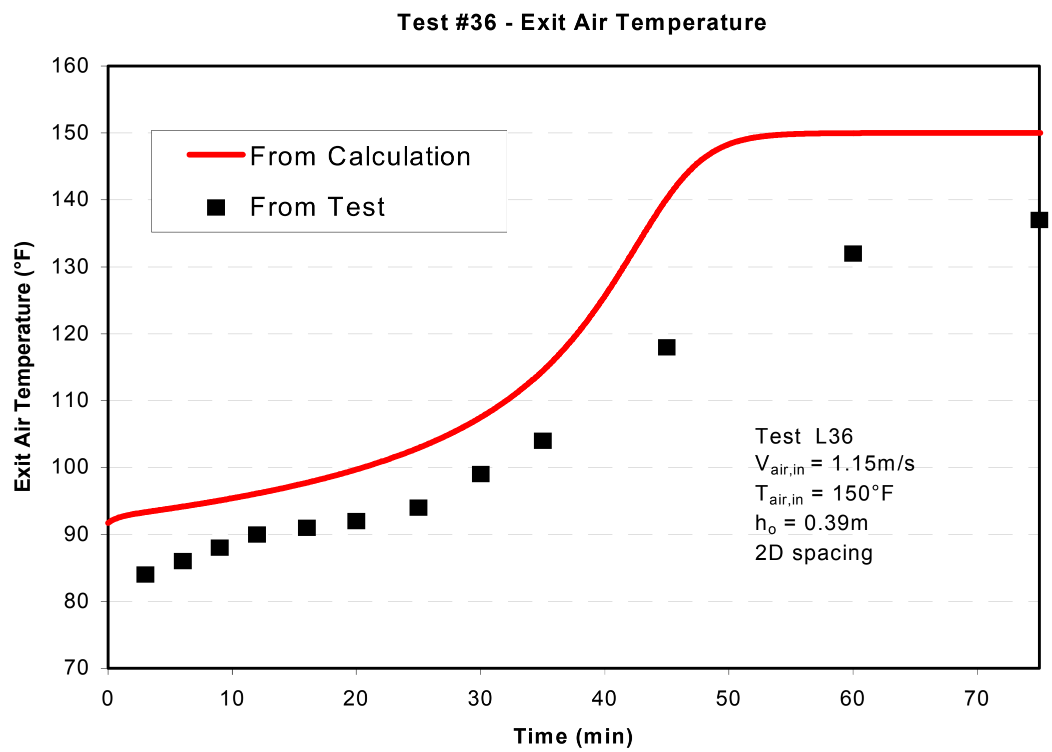

Figure 30: Exit Air Temperature Versus Time for Test 36. Comparison of Theory and Experiment.

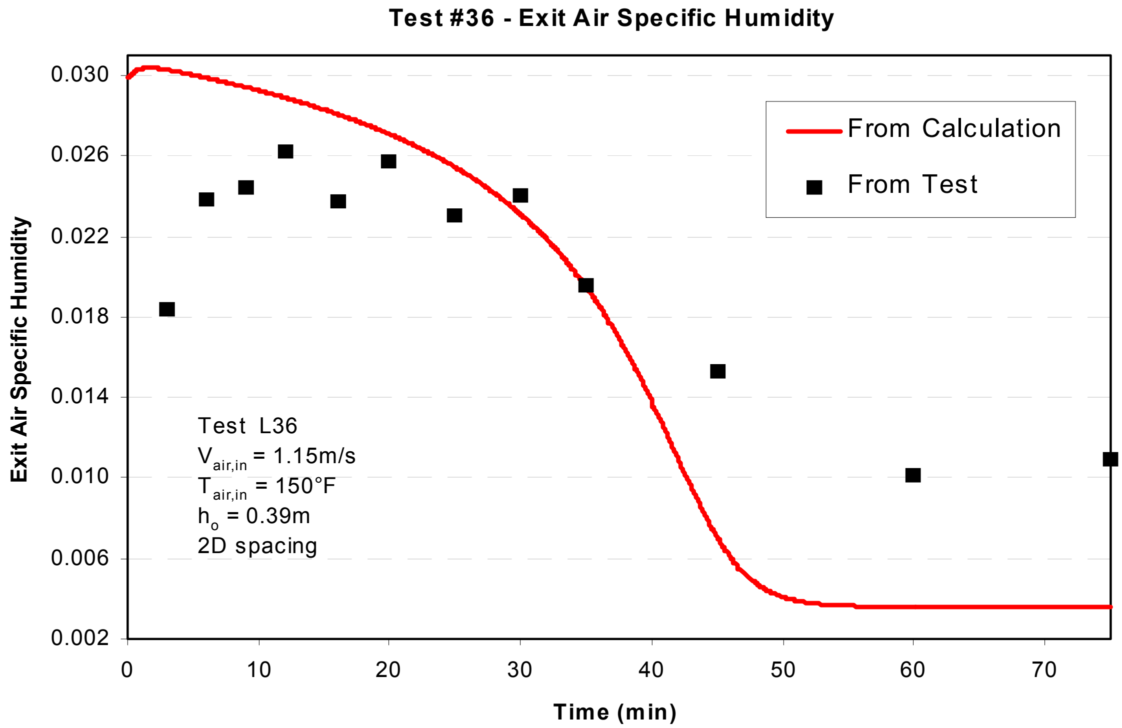

Figure 31: Exit Air Specific Humidity Versus Time for Test 36. Comparison of Theory and Experiment.

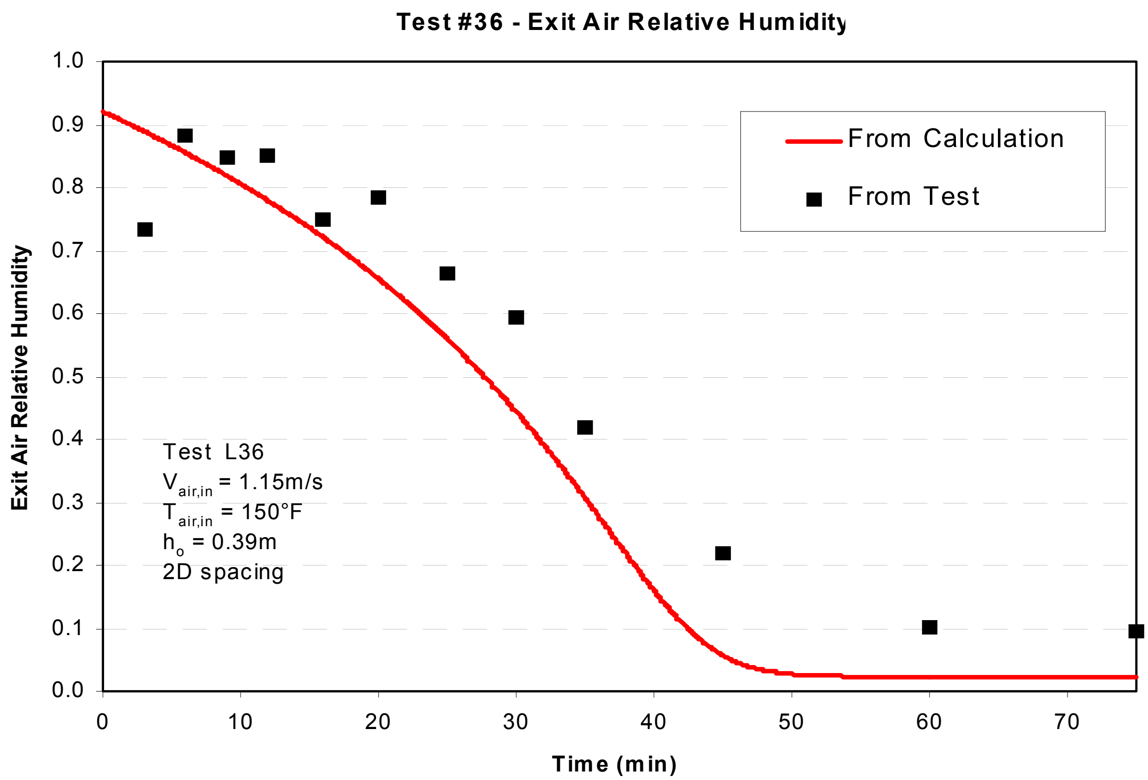

Figure 32: Exit Air Relative Humidity Versus Time for Test 36. Comparison of Theory and Experiment.

The comparisons are shown in a different way in Figures 33 to 35 as plots of the measured versus calculated parameters, for experiments representing the range of drying temperatures and air velocities tested. The results show excellent agreement on coal moisture and exit air temperature. The predicted values of specific humidity depart from the measured values at extremely low values of exit air humidity. Additional work is underway to validate and fine-tune the theoretical model.

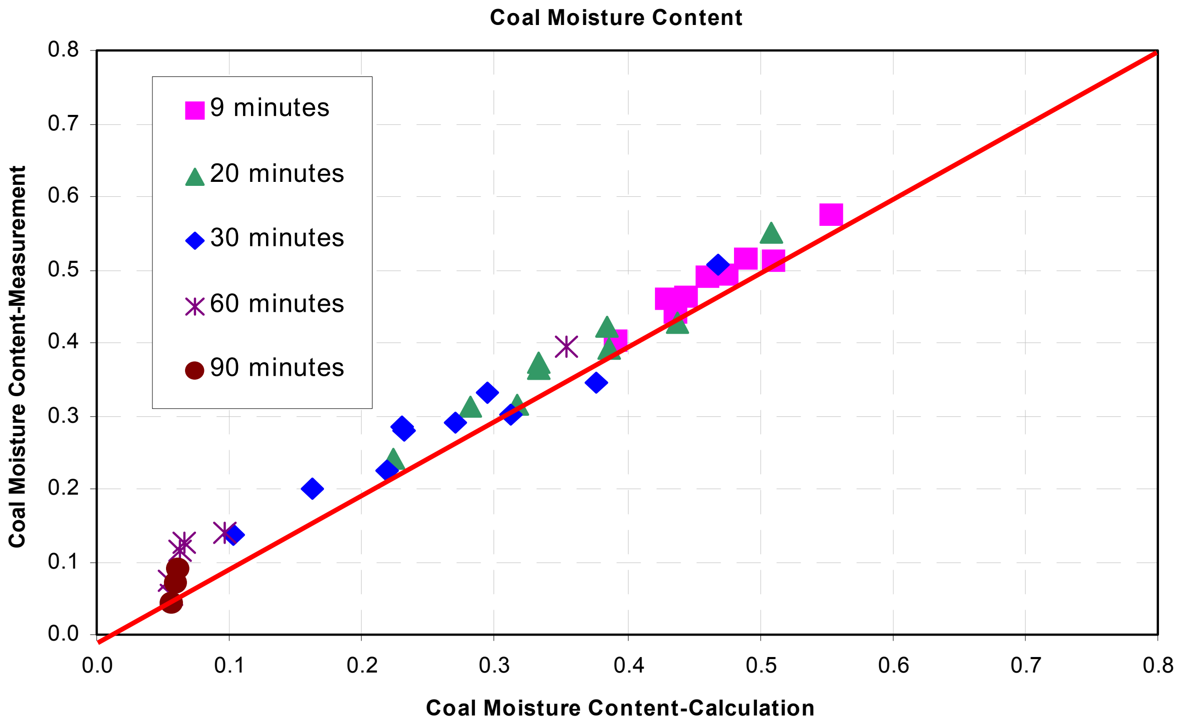

Figure 33: Comparison of Measured Versus Predicted Coal Moisture Content for Nine Sets of Data

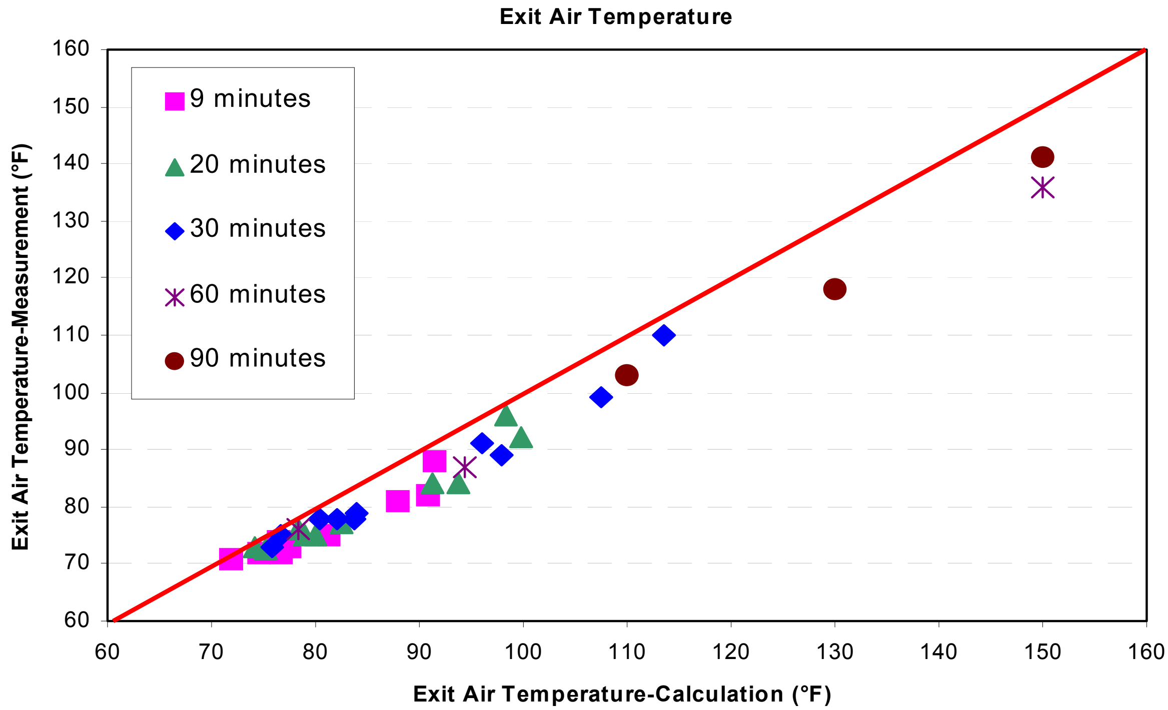

Figure 34: Comparison of Measured Versus Predicted Exit Air Temperature for Nine Sets of Data

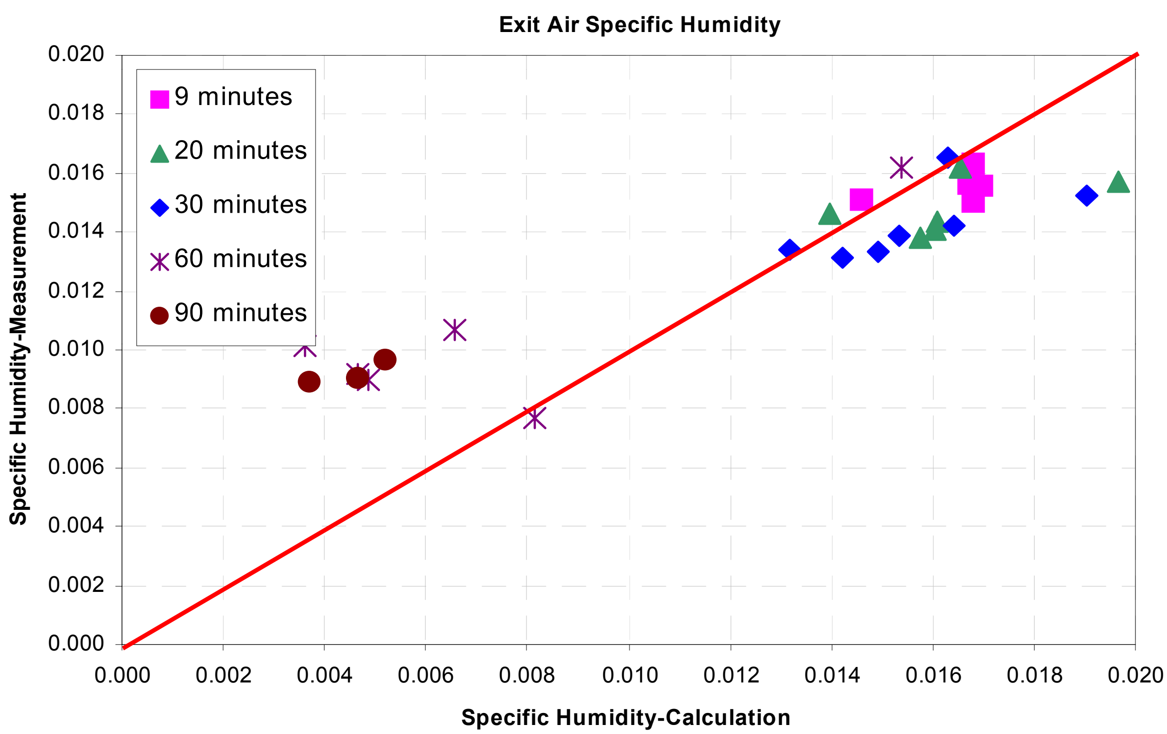

Figure 35: Comparison of Measured Versus Predicted Coal Moisture Content for Nine Sets of Data

CONCLUSIONS

Most of the effort during the first year of the project has focused on the effects of dryer process conditions on drying rate. Having this information is key to being able to design dryers for this application, to estimate the costs of the drying system equipment and its operating costs, and to estimate the impacts of drying on cost of energy. The experiments to date show that drying rate is a strong function of superficial air velocity, bed depth, drying temperature and heat flux from the in-bed heat exchanger to bed material. In particular, the data show that drying rate increases with increases in fluidization velocity, drying temperature and in-bed heat flux and with reductions in bed depth. Additional experiments will be conducted during the Fourth Quarter, 2003, to measure the effects of particle size and inlet air humidity on drying rate. Finally, fluidized bed drying experiments will be conducted with a Powder River Basin Coal.

Good progress was also made on Task 3 (Develop Drying Models and Compare to Experimental Data) during the last quarter. We developed a first-principle drying model based on the equations of conservation of mass and energy and equilibrium data on relative humidity versus coal moisture obtained from the Task 2 drying tests. The resulting system of ordinary differential equations was solved by a numerical integration technique. Solutions obtained to date are in excellent agreement with the measurements. Based on what has been completed so far, this model appears to be capable of accurately predicting rates of drying for a wide range of bed process conditions. Work is in progress to complete the validation and to fine-tune the model.

The additional experiments and analyses planned for Tasks 2 and 3 in the last few months of 2003 and in 2004 will provide the information on drying kinetics needed for carrying out the Task 4 and 5 Drying System Design Studies.

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2. Allardice, D. J., "The Water in Brown Coal," in The Science of Victorian Brown Coal: Structure, Properties and Consequences for Utilization ed. by R. A. Drurie; Butterworth-Heinemann, (1991).

3. Gauger, A. W., "Moisture in Coal" in Chemistry of Coal Utilization ed. by H. H. Lowry (1945).

NOMENCLATURE

A	Tube Bundle Surface Area
C_c	Specific Heat of Coal
C_L	Specific Heat of Coal Moisture
C_{pair}	Specific Heat of Air
d_p	Particle Size
hg	Enthalpy of Saturated H_2O Vapor
h_o	Settled Bed Depth
$\dot{m}_a$	Air Flow Rate
M_{DC}	Mass of Dry Coal
$M_{wet\ coal}$	Mass of Wet Coal
P	Absolute Pressure
P_{sat}	Vapor Pressure of H_2O
Q_{ave}	Average Heat Flux to Bed
$\dot{Q}_{LOSS}$	Rate of Heat Loss to Surroundings
$\dot{Q}_{TUBES}$	Rate of Heat Transfer in Tube Bundle
$T_{a,\ in}$	Air Inlet Temperature
T_b	Bed Temperature
u_L	Internal Energy of Coal Moisture
U_o	Superficial Air Velocity
V_{Bed}	Bed Volume
Y	Coal Moisture $\left(\frac{\text{kg } H_2O}{\text{kg } H_2O + \text{kg dry coal}}\right)$
ϕ	Relative Humidity
Γ	Coal Moisture $\left(\frac{\text{kg } H_2O}{\text{kg dry coal}}\right)$
$\dot{\Gamma}$	Drying Rate = $\frac{d\Gamma}{dt}$
ω	Specific Humidity of Air