# KINETICS OF COAL DRYING IN BUBBLING FLUIDIZED BEDS

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## ABSTRACT

Some coals used in U.S. coal fired power plants have unusually high moisture levels. High fuel moisture leads to low power plant thermal efficiency, increased stack emissions of pollutants and maintenance and operational problems. One solution is to dry the coal before burning it, and if this is done using power plant waste heat, it can result in significant efficiency improvements.

This paper describes laboratory experiments, to determine the kinetics of coal drying in a bubbling fluidized bed, and a simple theoretical model of coal drying. The experiments were performed with coal which had been crushed to minus 6 mm and fluidized with air with temperatures ranging up to 66°C and with velocities of 0.9 to 1.7 m/s. In-bed electrical heaters, used to simulate an in-bed tube bundle, provided additional thermal energy for drying. The experiments determined the effects of superficial air velocity, drying temperature and inlet air humidity level on rate of drying.

A theoretical model of the drying process was developed in which the air and coal particles are assumed to be at the same temperature and the air–water vapor mixture leaving the bed at the free surface is in equilibrium with the local values of particle moisture. This model is in good agreement with laboratory data, showing that for this application, the drying rates do not depend on fluidized bed bubble behavior or on particle- gas contact, but are controlled by in-bed heat transfer, flow rate, moisture content and temperature of the feed air, and the equilibrium moisture content of the coal.

KEYWORDS: Particle Drying, Bubbling Fluidization

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## I. BACKGROUND

Low rank fuels such as subbituminous coals and lignites contain relatively large amounts of moisture compared to higher rank coals. When these fuels are used in coal-fired power plants, the high fuel moisture affects the operation of the power plant, resulting in fuel handling problems, decreased power plant efficiency, and increased stack gas emissions and station service power. Recently completed theoretical analyses and coal test burns performed at a U.S. lignite-fired power plant showed that by reducing the fuel moisture, it is possible to improve boiler performance and generation efficiency and reduce stack emissions and water consumption by evaporative cooling towers (Reference 1). The economic viability of the approach and the actual impact of the drying system on efficiency, stack emissions and water consumption will depend critically on the design and operating conditions of the drying system. This paper describes laboratory drying studies performed by the authors to gather data and develop models on the drying kinetics of high moisture coals.

## II. LABORATORY DRYING STUDIES

The drying experiments were performed in a 152 mm diameter, 1372 mm high fluidized bed column with a sintered powder-metal distributor plate. The compressed air used in the experiments flowed though a rotameter and air heater before entering the plenum. A submerged horizontal bundle of 13 mm diameter electric heating elements, instrumented with thermocouples to indicate heater surface temperature, provided in-bed heating. Thermocouples inserted through the bed wall were used to measure vertical distribution of bed temperature. Small samples of coal were removed from the bed and coal moisture was measured at various time intervals during the batch bed drying tests.

The experiments were carried out with two coals, a North Dakota lignite and a subbituminous coal from the Powder River Basin (PRB). The as-received moisture content of the lignite varied slightly from sample-to-sample, usually ranging from 54 to 58 percent (expressed as mass of moisture/mass dry fuel) and the PRB coal had a moisture content of approximately 37 percent. During the first minute or two of each test, fines were elutriated from the bed. The drying rate 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.

The drying tests were performed with coal having a wide size distribution, in most cases with the top size in the 2 to 4 mm range and mean particle sizes from 300 to 400 microns. The tests were performed with inlet air and heater surface temperatures up to 66°C, with superficial air velocities ranging from 0.9 to 1.7 m/s and with settled bed depths of 0.39 m. The drying curves for two of the tests are given in Figure 1, where the numerical values for drying rate were obtained by fitting straight lines to the drying data over the first portions of the tests. Drying rate results for lignite are summarized in Figure 2, which shows the drying rate as a function of velocity, for four different particle sizes. The results show that the drying rate increased with air velocity, but that, within the accuracy of the data, the data for all four particle size distributions are on the same curve. Thus, the larger drying rates associated with the larger particles, are due to higher air velocities and not to any inherently higher rates of drying due to particle size. This suggests that, in this particle size range, drying rate is controlled by the internal pore structure of the coal, but not by particle size.

As to be expected, drying rate is also a strong function of temperature. Figure 3 compares drying rates for bed and inlet air temperatures ranging from 43 to 66°C.

## III. FIRST PRINCIPLE DRYING MODEL

The relative humidity of air in equilibrium with coal can be expressed as a function of the coal moisture content, Γ. Treybal (Ref. 2) presented adsorption data which are correlated well by

$$T \log f = f(\Gamma)$$

where T is absolute bed temperature and ϕ is relative humidity. As is seen in Figure 4, this gives a good fit of the data, with a relatively small scatter band.

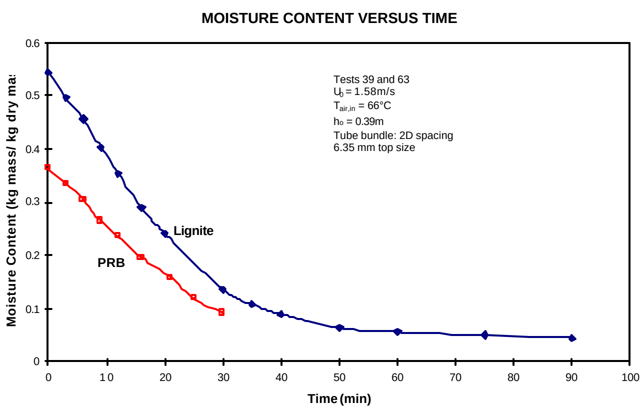


Fig. 1: Comparison of Drying Curves for Lignite and PRB Coals for a 66°C Drying Temperature

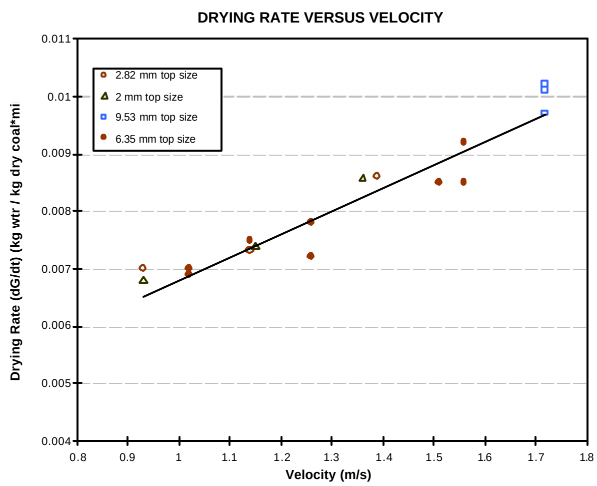


Fig. 2: Drying Rate as a Function of Superficial Air Velocity and Particle Size

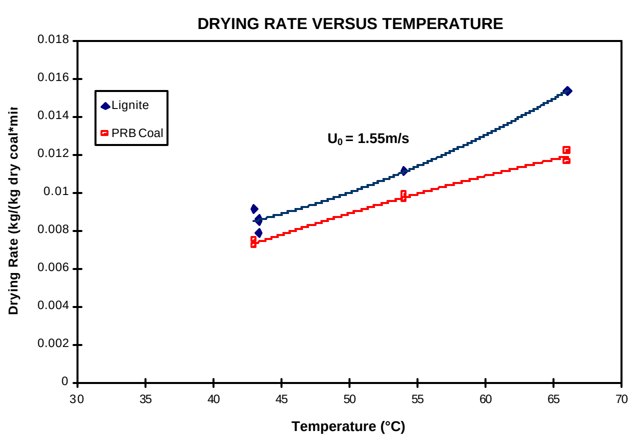


Fig. 3: Comparison of Drying Rates for Lignite and PRB. Effect of Bed and Inlet Air Temperature

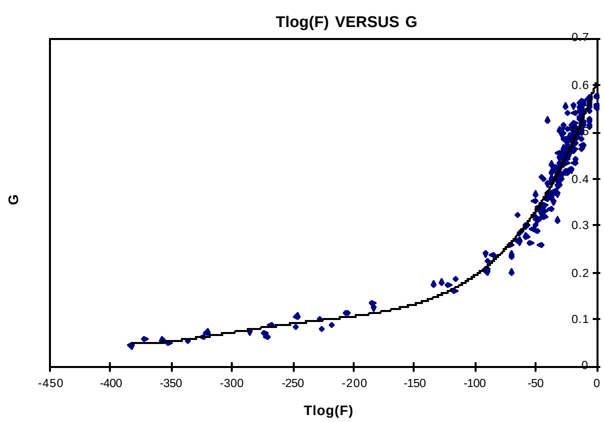


Fig. 4: Equilibrium Relative Humidity of Air Versus Moisture Content of Lignite

The equilibrium moisture content-relative humidity relationship, described in Figure 4 was used, along with the equations of conservation of mass and energy, to develop a first principle model of the drying process. The model assumes at any instant of time, the particles and air in the bed are at the same temperature and the gas and particle properties do not vary with vertical distance in the bed. Thus for the batch bed drying process illustrated in Figure 5, conservation of mass and energy can be written:

$$\frac{d\Gamma}{dt} = -\frac{\dot{m}_a}{m_{DC}}\left(w_2 - w_i\right) \qquad \text{Eq. 1}$$

$$\dot{Q}_{TUBES} - \dot{Q}_{LOSS} = m_{DC}\left[\left(C_C + \Gamma C_L\right)\frac{dT_2}{dt} + u_L\left(-\frac{\dot{m}_a}{m_{DC}}\right)\left(w_2 - w_1\right)\right] + \dot{m}_a\left[C_{pa}\left(T_2 - T_1\right) + w_2 hg_2 - w_1 hg_1\right] \qquad \text{Eq. 2}$$

Specific humidity, $\omega$, can be related to relative humidity $\phi$ and air temperature T, by

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

while the relative humidity is an empirical function of coal moisture $\Gamma$ (Figure 4).

In addition, the tube bundle heat transfer rate is

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

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

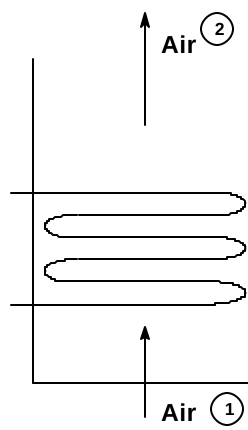


Fig. 5: Sketch of Dryer Model

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

Figures 6-9 show a comparison of the model with one set of drying data. The degree of agreement shown here is typical of the agreement obtained for the experiments with other bed operating conditions. The model is an equilibrium model and does not utilize information on bed bubbling behavior, particle-gas contacting nor mass transfer within the particle pores. For the range of fluidization conditions encountered in this process, a simple equilibrium model works very nicely.

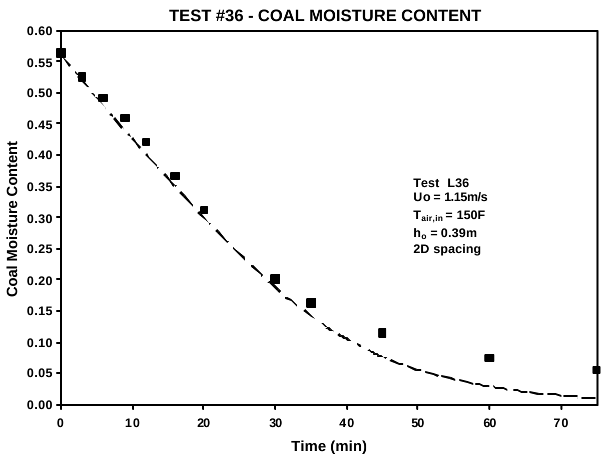


Fig. 6: Lignite Drying Curve for Test 36 – Comparison Between Theory and Experiment

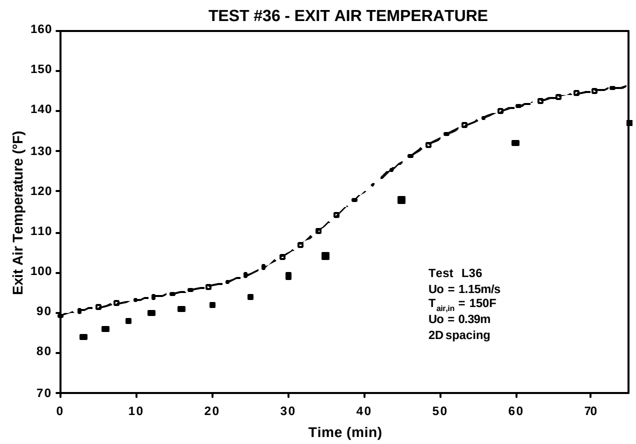


Fig. 7: Exit Air Temperature for Test 36 – Comparison Between Theory and Experiment

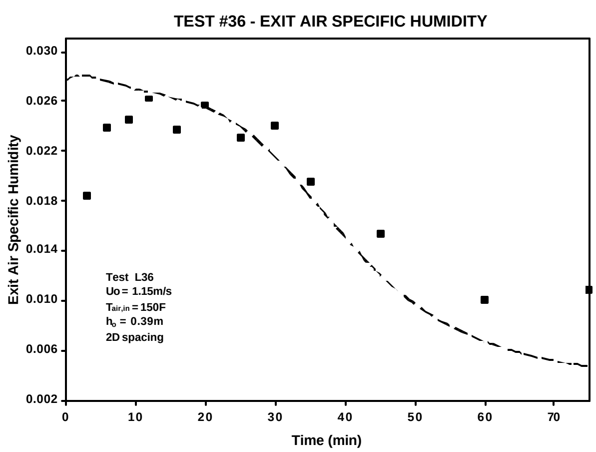


Fig. 8: Exit Air Specific Humidity for Test 36 – Comparison Between Theory and Experiment

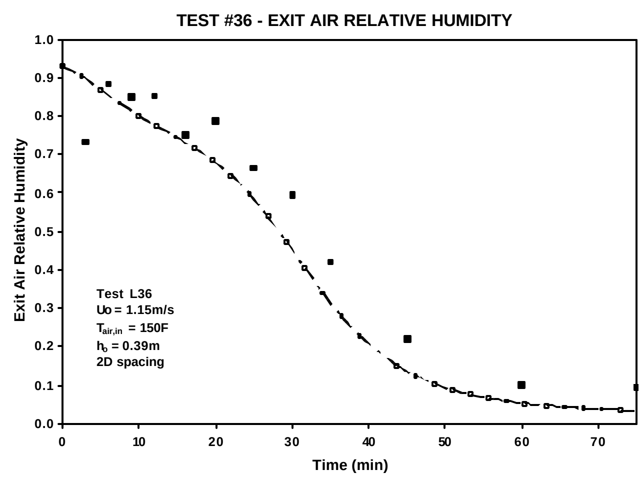


Fig. 9: Exit Air Relative Humidity for Test 36 – Comparison Between Theory and Experiment

## IV. CONCLUSIONS

Laboratory experiments were performed on crushed high moisture coal to determine the effects of fluidization velocity, particle size, bed temperature and coal rank on rate of drying. The data show that drying rates do not depend on fluidized bed bubble behavior or on particle-gas contact, but instead are controlled by in-bed heat transfer, flow rate, moisture content and temperature of the feed air, and the equilibrium moisture content of the coal. The theoretical model of the drying process described in this paper is in excellent agreement with the laboratory data. The model assumes the bed is well-mixed, with the air and coal particles being at the same temperature. The model also assumes the air-water vapor mixture leaving the free surface of the bed is in equilibrium with the local values of particle moisture.

## V. ACKNOWLEDGEMENTS

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## VI. NOMENCLATURE

| | |
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| $C_c$ | 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 |
| $\dot{m}_a$ | Flow Rate of Dry Air |
| P | Absolute Pressure |
| $P_{sat}$ | Vapor Pressure of $H_2O$ |
| $\dot{Q}_{LOSS}$ | Rate of Heat Loss to Surroundings |
| $\dot{Q}_{TUBES}$ | Rate of Heat Transfer in Tube Bundle |
| $T_1$ | Air Inlet Temperature |
| $T_2$ | Bed Temperature |
| $u_L$ | Internal Energy of Coal Moisture |
| $U_o$ | Superficial Air Velocity |
| $\phi$ | Relative Humidity |
| $\Gamma$ | Coal Moisture $\left(\frac{\text{kg } H_2O}{\text{kg dry coal}}\right)$ |
| $\dot{\Gamma}$ | Drying Rate = $\frac{d\Gamma}{dt}$ |
| $\omega$ | Specific Humidity of Air |