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Laboratory investigation of drying rates of Illinois coals

Wei-Cheng Wang
Lehigh University

Wang, Wei-Cheng

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Laboratory Investigation of Drying Rates of Illinois Coals

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Wei-Cheng Wang

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Dr. Edward K. Levy
Thesis Advisor

Dr. Herman F. Nied
Chairperson of Department

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List of Symbols

Symbol	Chapters	Description
dp	2	Particle diameter
Xi	2	Weight fraction
Ai	2	Surface area of a particle
Vi	2	Volume of a particle
Umf	2	Minimum fluidization velocity
t*	3	Web bulb temperature
t	3	Dry bulb temperature
Ws^*	3	Saturation humidity ratio
P	3	Total mixture pressure
Pws	3	Partial pressure of water vapor
ϕ_2	3	Exit air relative humidity
μ	3	Degree of Saturation
h	3	Heat transfer coefficient
$\dot{Q}_{heater}$	3	Power of heaters
A_h	3	Area of heaters
T_{heater}	3	Temperature of heaters
T_{bed}	3	Average bed temperature
Γ	4	Coal moisture content
T_2	4	Exit air temperature
ω_2	4	Exit air specific humidity
m_{dc}	4	Mass of dry coal
m_L	4	Mass of liquid
u_{dc}	4	Internal energy of dry coal
u_L	4	Internal energy of liquid
Q_{loss}	4	Heat loss
m_a	4	Mass of dry air
m_v	4	Mass of Vapor
h_a	4	Specific enthalpy of air
h_v	4	Specific enthalpy of vapor
C_c	4	Specific heat of coal
C_L	4	Specific heat of liquid

List of Symbols

$\dot{m}_a$	4	Flow rate of dry air
C_{pa}	4	Specific heat of air
T_1	4	Inlet air temperature
h_g	4	Enthalpy of saturated vapor
ω_1	4	Inlet air specific humidity
P_{g2}	4	Saturation pressure

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Abstract

High moisture coal leads to low power plant efficiency, increased stack emissions of pollutants and maintenance and operational problems when it is used in coal fired power plants. In this study, laboratory experiments and theoretical calculations of the coal drying process were carried out and compared in order to determine proper drying conditions.

This research describes several experiments to present the effects of parameters, such as drying temperature, on drying performance. The tests were carried out with three different coals - Buckheart, Crown mine and Viper mine, which have initial moisture contents of 23%, 18% and 20%, respectively. The drying tests were performed from 1.1m/s to 1.2m/s air velocity and from 110°F to 140°F drying temperature. In this paper, the effect of drying temperature on drying rate of different coals was studied to obtain information relating to optimal operating conditions. The drying performances for each coal can be determined by analyzing the test data and operation conditions.

The author also utilized a theoretical model for the drying process based on mass balances and conservation of energy. Comparisons were made between experimental and theoretical results. Good agreement with laboratory test results was obtained especially in lower drying temperature. It is shown that this model can be reasonably used to predict the drying performance.

Chapter 1 Introduction

Some coals used in U.S. coal fired power plants have unusually high moisture levels. When this coal is used in coal-fired boilers, the high moisture affects the operation of the power plant, results in the reduction of power plant efficiency and the increase of stack gas emission and station service power. It also affects heat rate, mass rate of emissions and the consumption of water needed for evaporative cooling.

Recent research work concerns about the impact of coal moisture content on boiler efficiency and cooling water makeup flow from an evaporative cooling tower (Ref. 1). The theoretical analysis and experimental results show that drying the coal from 40 to 25 percent moisture can reduce makeup water flow rate by 5 to 7 percent while the average reduction in auxiliary power as fans and mill was reduced by 3.8 percent. Drying the coal from 37.5 to 31.4 percent can improve the boiler efficiency by about 2.6 percent and the net unit rate by 2.7 to 2.8 percent. 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. Another study also shows lower mass emissions of CO_2 and SO_2 when coal moisture content is low (Ref. 2). Besides, another research (Ref. 3) shows that approximately 80% excess air is required to prevent smoke formation for moist coals. For dry coals, only 30% excess air is required. Using less excess air reduces sensible heat losses with the flue gases, increasing boiler efficiency. Another reason for a higher overall boiler efficiency is the lower flue gas temperature to the stack. In a boiler without coal drying, the flue gas temperature might be 350°F or higher, but with a dryer this temperature will be closer to 220°F coming out of a dryer. The overall thermal efficiency increases can amount to 5%-15%, with steam production increases of 50-60%. These studies show the benefits of reducing the coal moisture content in power stations.

Energy efficiency in drying can be improved by using recirculating exhaust gases. The air leaving a directly heated air dryer is usually not saturated, so some of the hot exhaust gas can be recirculated to the inlet of the dryer. Because it is still warm, energy is not needed to heat it, increasing the drying efficiency. (Ref. 3) In addition, power stations generate a large amount of low quality heat which is removed by cooling water from the condenser. 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. The thermal efficiency of the boiler will be increased while thermal pollution is decreased.

In an earlier paper (Ref. 4), the authors also presented that low rank coal can be dried in a fluidized bed using low grade waste heat with coal residence time which are short enough to make the drying process practical and economic for power plant use. The approach for doing this is making use of the hot circulating cooling water leaving the condenser to provide the thermal energy used for coal drying. The temperature of the circulating water leaving the condenser is usually about 120°F, and this can be used to produce an air stream at approximately 110°F. Therefore, the coal drying performance, which is drying rates, at this range of temperature was studied to see if the coal can be dried effectively.

The drying rates of the coal depend critically on the design and operating conditions of the drying system, which are drying temperature, mass of coal in the reaction, drying air velocity, bed depth, the equilibrium moisture content of the coal, in-bed heat flux and inlet air humidity, but not on fluidized bed bubble behavior or on particle-gas contact (Ref. 5). P. P. Thomas (Ref. 6) used two kinds of fluidized beds-batch and continuous, to dry granular cellular materials. The experimental results show that the critical moisture content depends on the velocity and temperature of the heating medium, as well as the particle size and mass of solids. With the moisture content of 62 to 66%, the drying rate of these materials is enhanced by an increase in the feed temperature of the air or an increase in its flow rate. It is reduced by an increase in the particle size or an increase in solids inventory. Julia ZH Gao et al. (Ref. 7) shows that inlet air velocity can play a critical role in maintaining proper fluidization and ultimately, uniform drying. W.K. Ng et al. (Ref. 8) carried out an optimization study of fluidized bed drying, using an industrial-scale fluidized bed dryer. The results show that the drying rates are approximately 10 to 12% higher as the fluidization velocity increased from 1.5 Umf to 2 Umf. On the other hand, the drying temperature is also an important factor during drying process. Higher drying temperatures imply greater driving forces for the heat transfer. P. K. Agarwal et al. (Ref. 9) conducted an important model for coal drying. His results show that the drying time decreases significantly when the drying temperature increase. In addition, the equilibrium moisture content in the final product may be lower for a higher drying temperature. The results also show describe that the size of coal particles influences significantly the time required for the particles to reach a steady state. In the report of coal drying written by Levy and Caram et al. (Ref. 10), the drying rates of two coals (PRB and lignite) were compared at different drying temperatures. The results show that with the same general characteristics, the drying rate of PRB was 14 to 20 percent lower than lignite. Both of the drying rates were reduced when the drying temperature was decreased.

This research deals with three coals, Buckheart, Crown mine and Viper mine. Typically, the moisture content of Buckheart is 23 percent, where Crown mine and Viper mine are 18 and 20 percent, respectively. Three of them are expressed on a dry coal basis, as Kg H_2O/ Kg dry coal. If we consider the wet coal basis, as Kg H_2O/ Kg wet coal, the moisture content of Buckheart, Crown mine and Viper mine are 19 percent 15 percent, and 17 percent, respectively.

An experimental investigation on drying of Buckheart, Crown mine and Viper mine under batch fluidization was carried out in this study. By doing experiments in a lab scale fluidized bed, the drying conditions of the industrial drying equipment can be easily simulated. The performance of coal drying reached in the laboratory will provide useful information for optimum drying operation and for building an optimum dryer in coal-fired power plants. The significant facts that can affect the drying performance are drying temperature, mass of coal in the reaction, drying air velocity, bed depth, inbed heat flux, and inlet air humidity. In this thesis, the effect of the flow rate and drying temperature of the drying medium for three different coals are studied.

In this paper, a theoretical model of the drying process was used 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. The model was compared with experimental data in different drying conditions. With the completion of experimental work and theoretical analyses, the variation of drying rate versus the drying parameters can be found and the prediction of drying process will be certainly obtained.

Chapter 2 Experimental Description

2.1 Experimental Setup

The drying experiments were performed in the Energy Research Center's Fluidized Bed Laboratory as shown in Fig 2.1. The steel bed has a height of 15 inches and a diameter of 6 inches. A 5 feet Plexiglas tube was attached above the metal bed. A 4.3-inch-diameter metal duct was connected to the Plexiglas tube. The duct ended with a filter bag to capture elutriated particles. The compressed air used in the experiments flowed though a rotameter and air heater before entering the plenum. Thermocouples inserted through the bed wall were used to measure vertical distribution of bed temperature. A horizontal bundle of eighteen 0.5 inches diameter electric heating elements is used to provide in-bed heating. The heaters are located in the region from 3 inches to 12 inches above the distributor (Fig 2.2) 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 100°F to 140°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.

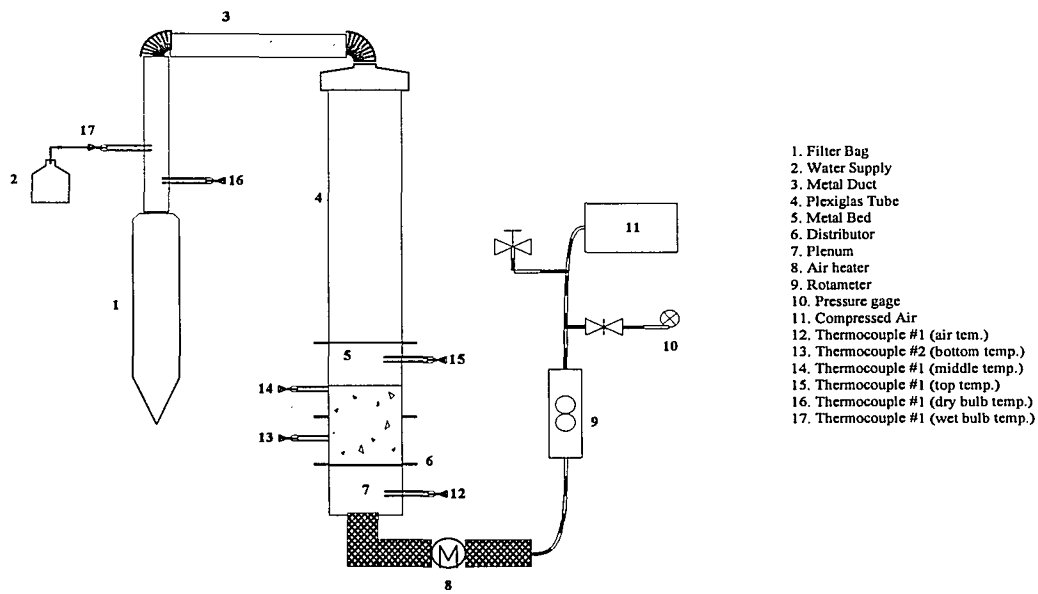

Figure 2.1 Sketch of the experimental apparatus

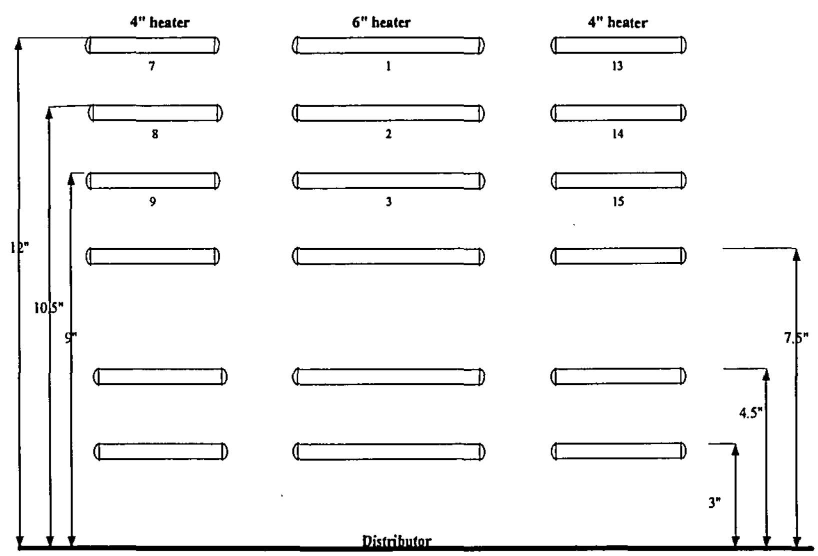

Figure 2.2 In-bed heaters distribution

2.2 Coal particle size distribution

To analyze further for the drying mechanisms involved in the effective mean particle diameter, dp had to be calculated. The effective mean particle diameter is the term which has the most relevance to fluid and particle mechanics, since it is based on an equivalent diameter. The mean particle sizes, defined as (Ref. 11, Ref. 12)

$$dp = \frac{6}{\sum X_i(\frac{A_i}{V_i})} = \frac{6}{\sum X_i(\frac{6}{dp_i})} = \frac{1}{\sum \frac{X_i}{dp_i}} \qquad (1)$$

Figure 2.3, 2.4 and 2.5 present the particle size distributions for the Buckheart, Crown mine, and Viper mine coals. The top size of these three coals is 0.25 inches.

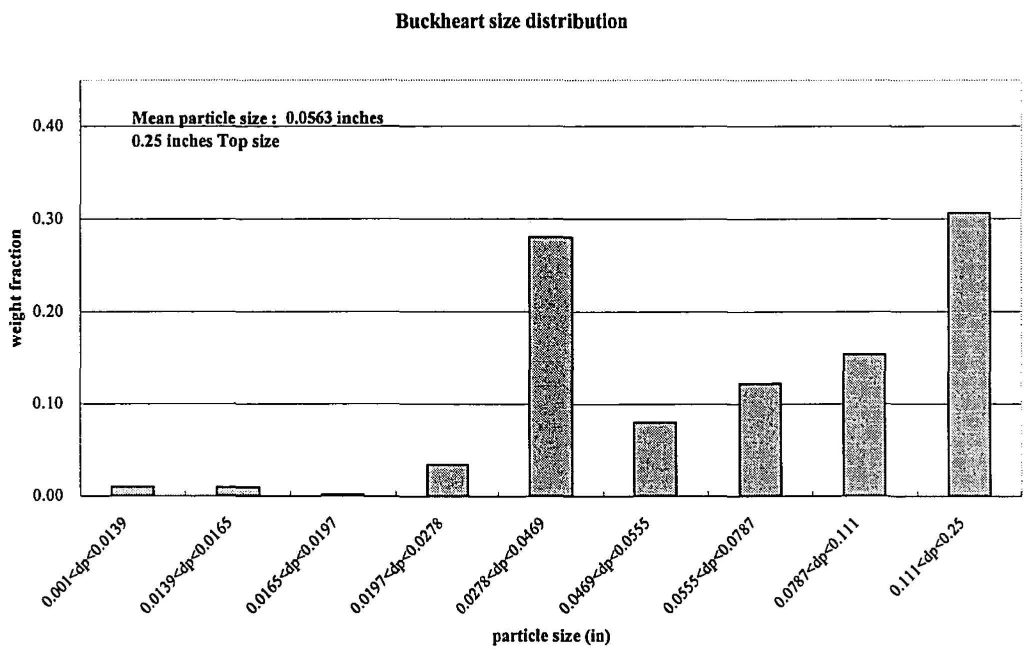

Figure 2.3 Buckheart particle size distribution

C

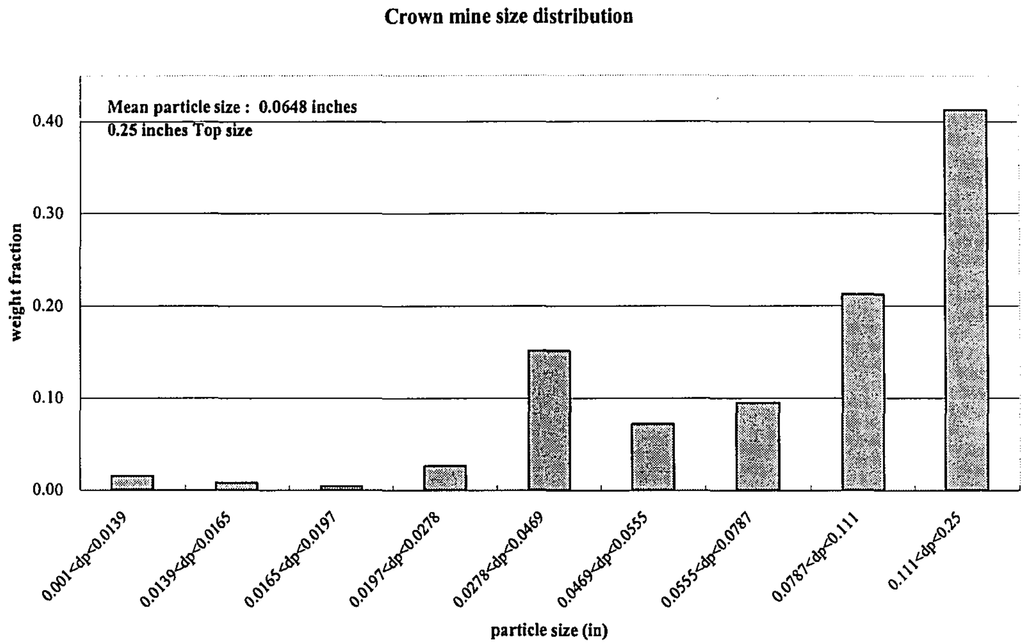

Figure 2.4 Crown mine particle size distribution

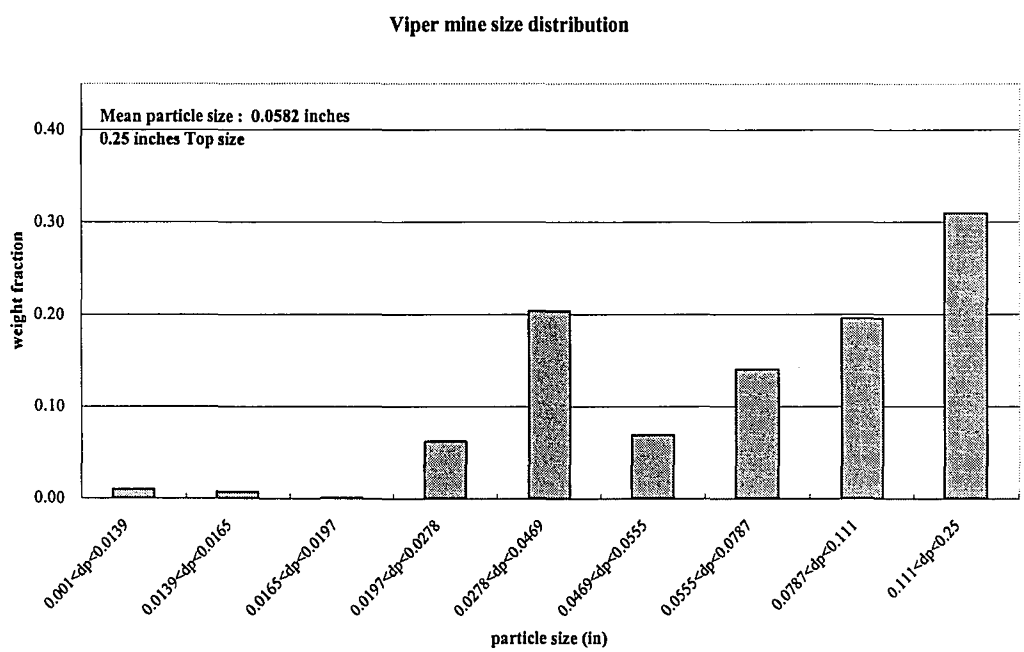

Figure 2.5 Viper mine particle size distribution

2.3 Minimum Fluidization Velocity Measurement

The flow rates at which a bed is expanded to such a degree that the particles may move within the bed is known as the onset of fluidization or fluidization point, and the bed is referred to as an incipiently fluidized bed. When mixing occurs, because of the high degree of turbulence, temperatures are quickly attained throughout the system. Large instabilities with bubbling and channeling of gas occur when the flow rate is increased above the minimum fluidization velocity. (Ref. 11)

The minimum fluidization velocity (Umf) is the superficial velocity point where the bed pressure drop reaches the maximum value and remains constant (Ref 11). Figure 2.6 to Figure 2.8 show the pressure drop of bed under different fluidization velocities for the Buckheart, Crown mine and Viper mine coals. These results show that Umf ranged from 1.1 to 1.25 m/s.

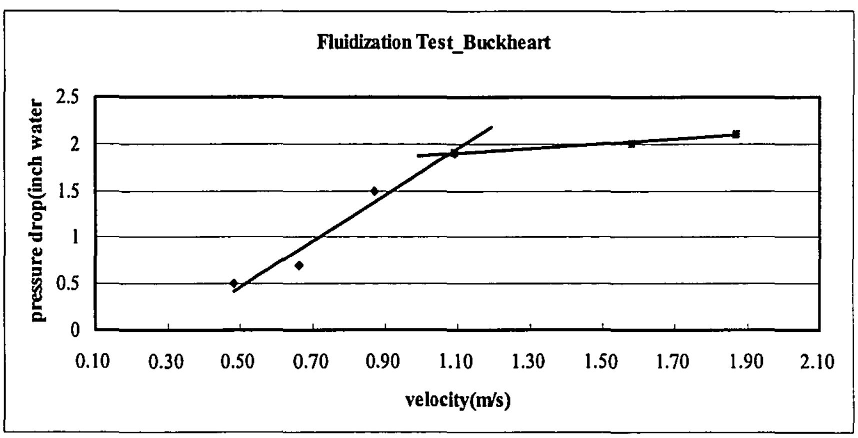

Figure 2.6 Bed pressure drop versus velocity _ Buckheart

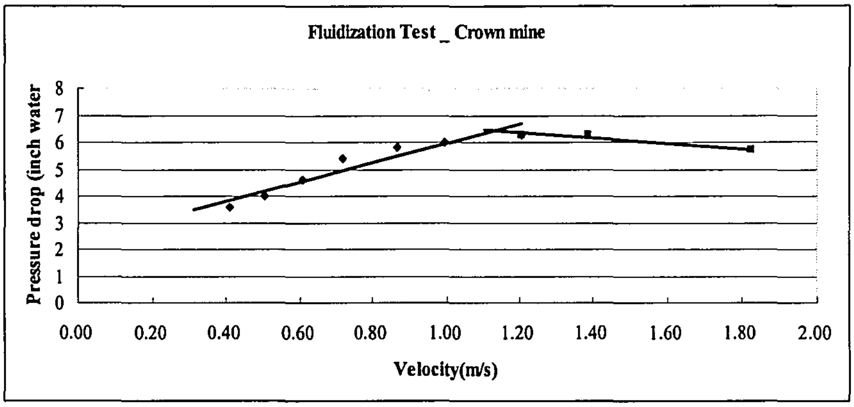

Figure 2.7 Bed pressure drop versus velocity _Crown mine

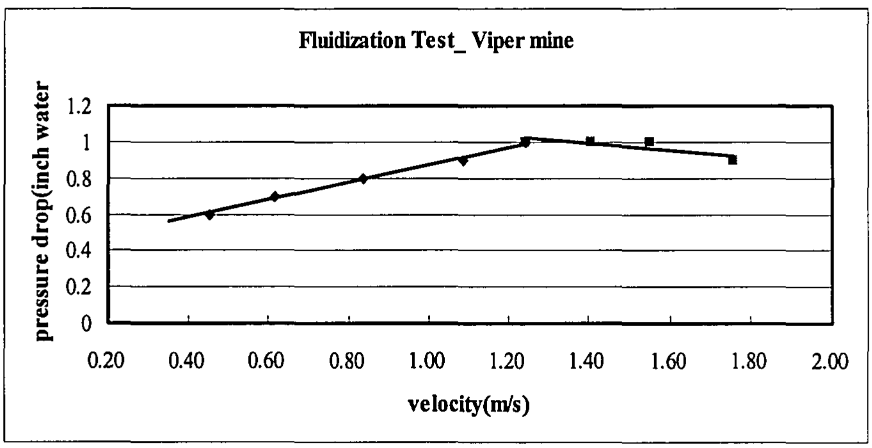

Figure 2.8 Bed pressure drop versus velocity_ Viper mine

2.4 Drying Test Procedure

The drying tests were performed with specific humidity of the inlet air ranging from 0.007 to 0.009. Small samples of the coal were removed from the bed periodically during the tests and coal moisture content was measured. The complete test procedure used in these experiments is detailed in Figure 2.9.

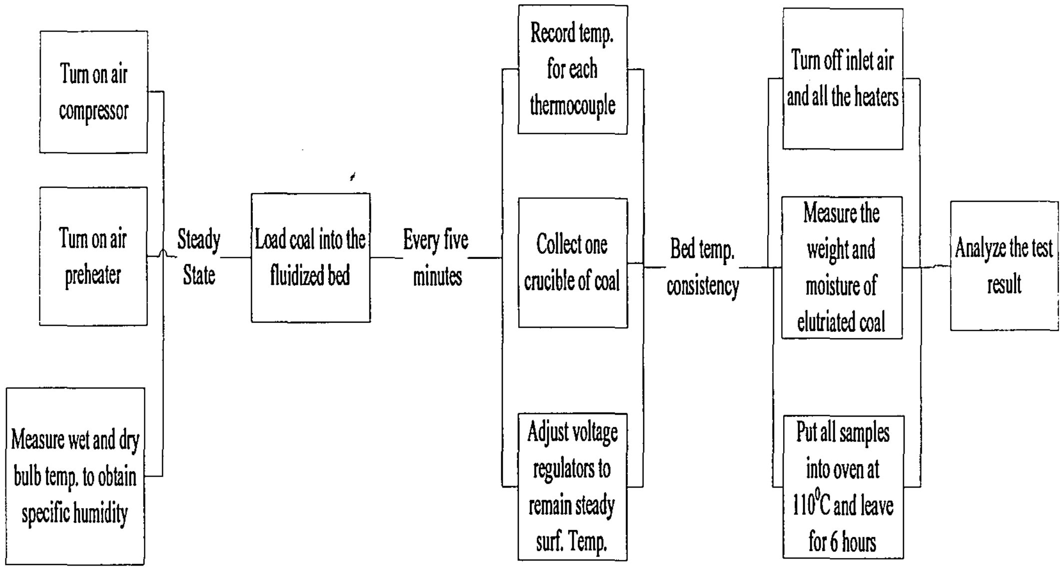

Figure 2.9 Drying test procedure

Chapter 3 Experimental Results

The drying tests were done over a range of conditions. Both inlet air temperature and surface temperature were the same during a test, with these values ranging from 110°F to 140°F. According to the fluidization experiments, the Umf of the Buckheart, Crown mine and Viper mine coals are 1.2 m/s, 1.1m/s and 1.25 m/s, respectively. The initial bed mass for the Buckheart is 4 kg, which has 12.5 inch bed depth. For the Crown mine and Viper mine, the initial mass is 2.5 kg, with 8 inch bed depth. The initial moisture contents ranged from 18% to 23% (kg water/ kg dry coal). All the tests were performed with the coal which had a 1/4 inch top size.

3.1 Moisture reduction curves

The extent to which coal can be dried depends on the way the moisture is associated with it, and hence knowledge of the moisture-solid equilibrium is an important aspect when considering drying processes. A coal drying curve is the best characterization of the simultaneous heat and mass transfer between the coal and hot air drying medium. (Ref. 13) The curve can also be used directly to determine the time required for drying larger batches under the same drying conditions. Figure 3.1 shows the moisture content reduction of Buckheart within 45 minutes of drying time for two different drying temperatures. The moisture contents decreased more rapidly at higher temperature. The same results can be seen in the Crown mine and Viper mine coals (Figure 3.2 and 3.3). The time to attain equilibrium moisture content is reduced when increasing drying temperature. N.C. Diamond et al. (Ref. 14) had the same results when carrying out lignite drying in a fluidized bed.

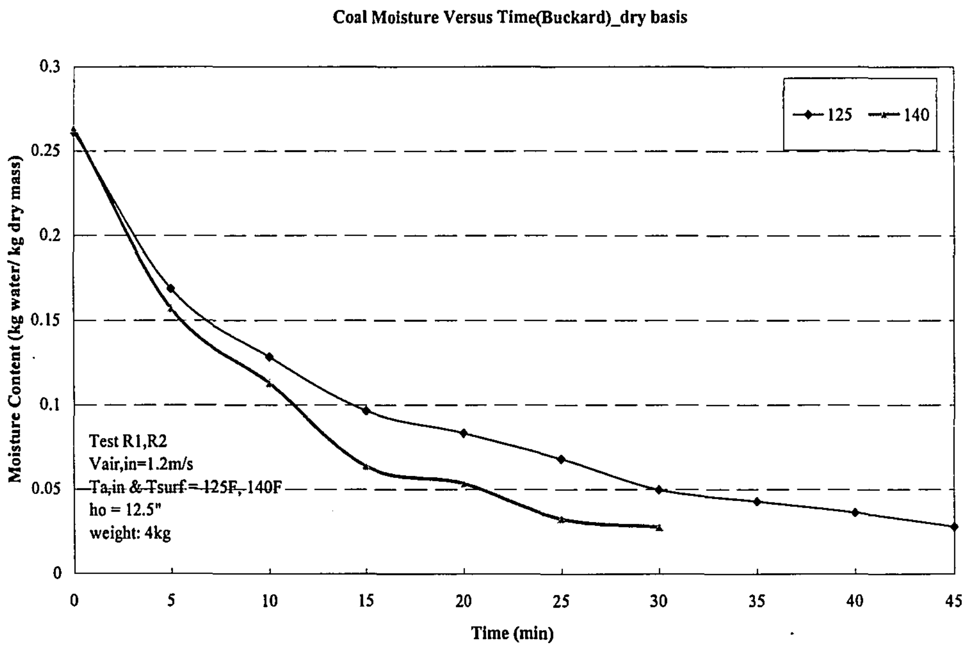

Figure 3.1 Moisture content versus time _ Buckheart

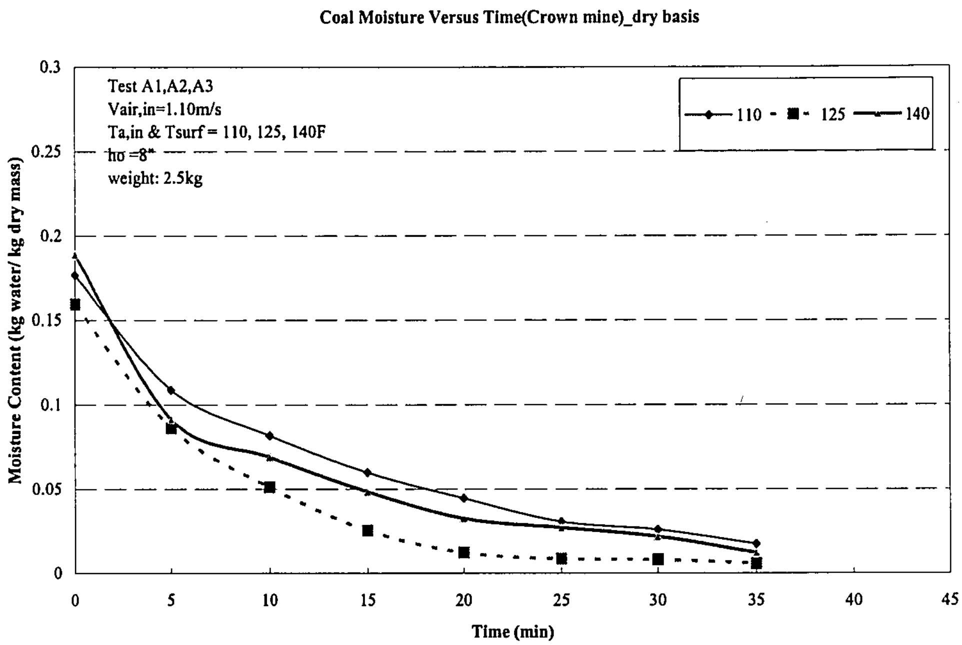

Figure 3.2 Moisture content versus time _ Crown mine

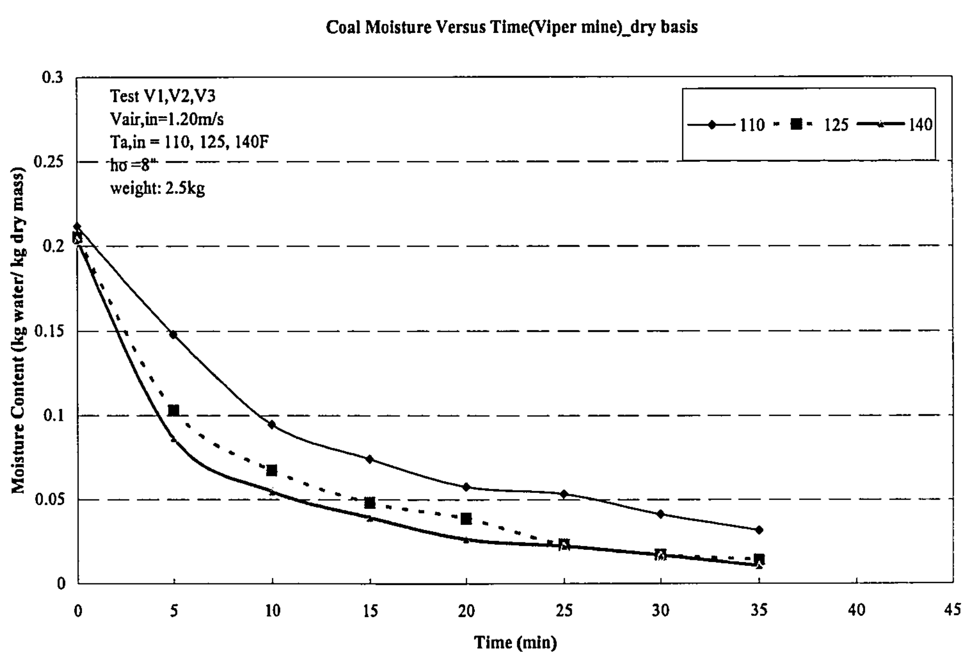

Figure 3.3 Moisture content versus time _ Viper mine

3.2 Drying rates

The slopes of the drying curves indicate the rate of drying (Ref. 5). The characteristics of drying behavior show that the drying rate is reduced after 5 to 10 minutes. Figure 3.4~3.6 present the drying rates of Buckheart, Crown mine, and Viper mine in the first 5 minutes. The drying rates were enhanced by increasing the drying temperature. Especially in the tests of Viper mine (Fig 3.6), the drying rate increased 40% when drying temperature was increased from 110°F to 140°F.

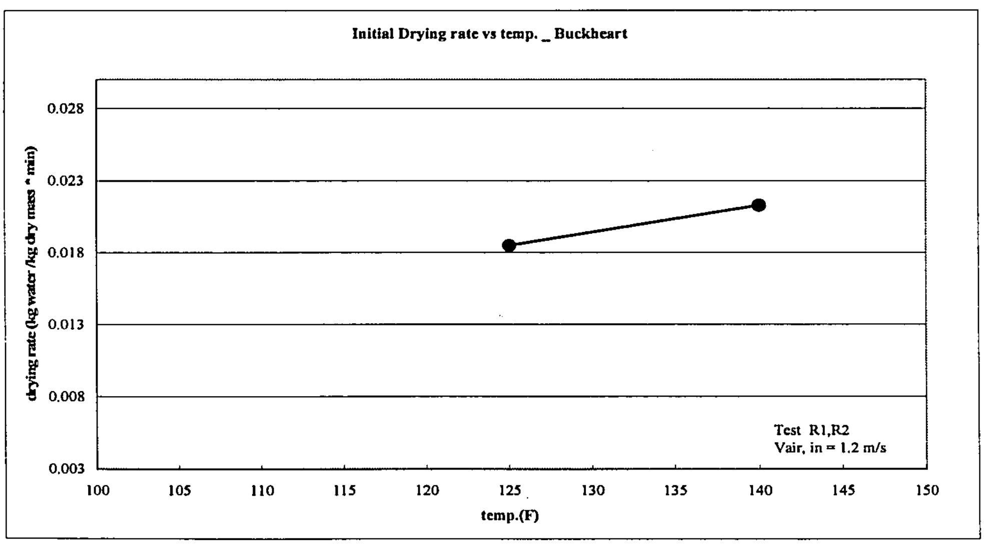

Figure 3.4 Initial drying rates versus temperature_ Buckheart

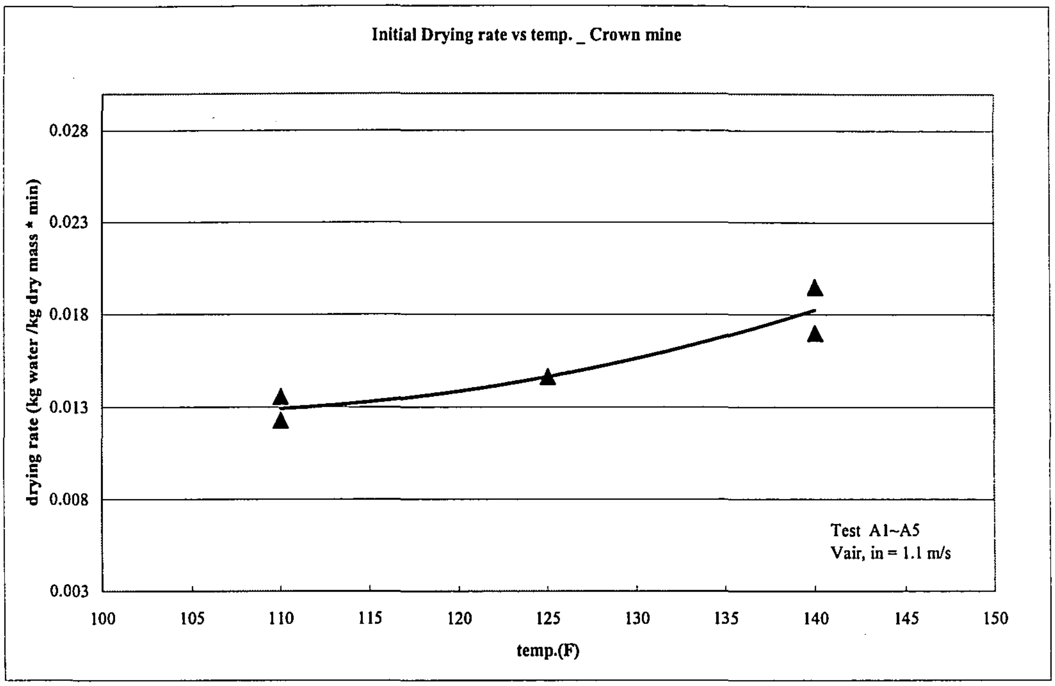

Figure 3.5 Initial drying rates versus temperature_ Crown mine

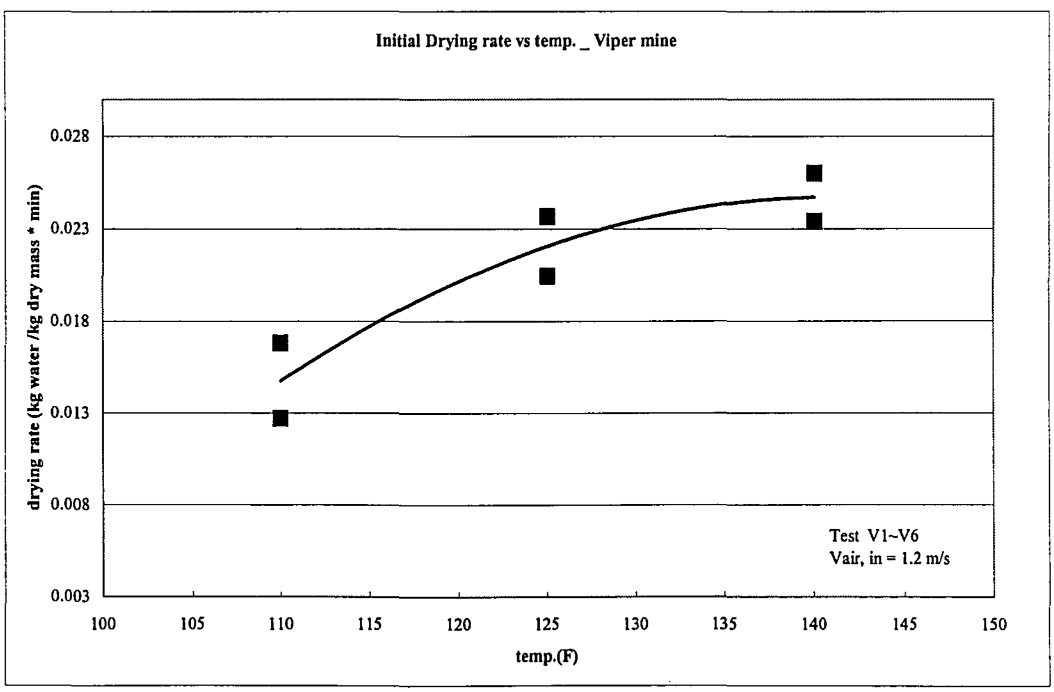

Figure 3.6 Initial drying rates versus temperature_ Viper mine

3.3 Exit air temperature

To determine the equilibrium state of the drying medium, exit gas temperature was measured periodically. The exhaust air temperature can be used to detect poor fluidization. If the exit air temperature rises more rapidly than anticipated, it is an indication that fluidization is incomplete. (Ref. 7) The exit air temperature changed with time for the Buckheart, Crown mine and Viper mine coals as is shown in Fig 3.7 to 3.9. These tests were done by three different drying temperatures - 110°F, 125°F and 140°F. Obviously, the exhaust air temperature rises gradually with time. The trend was similar to the result obtained by Joao F. A. Vitor et. al.(Ref. 15). The exit air temperature increased more rapidly when drying temperature was increased.

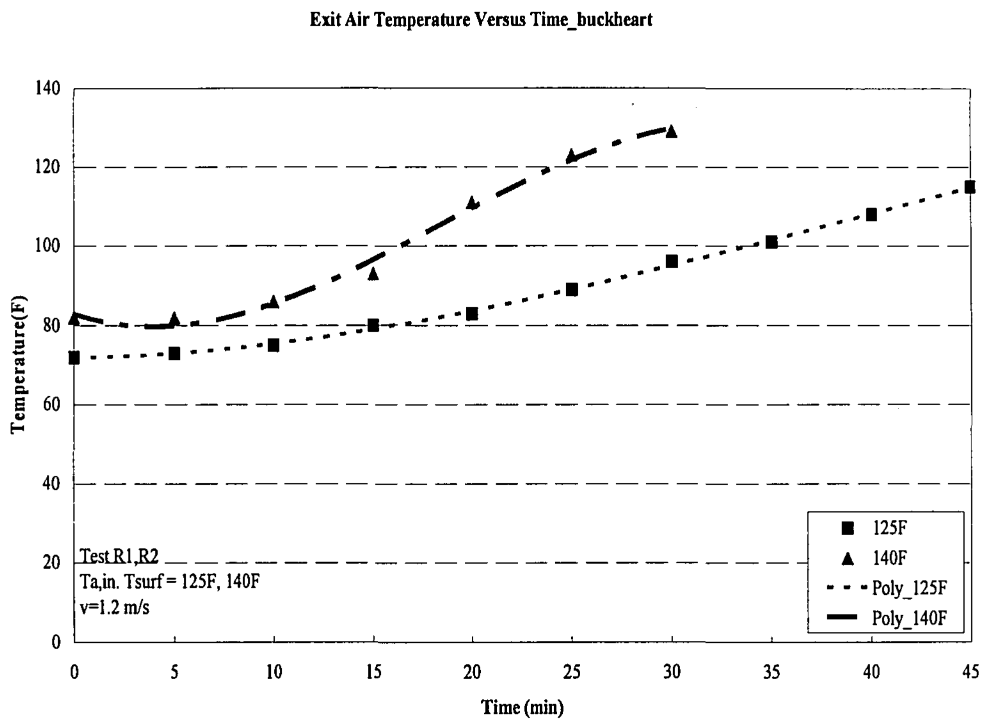

Figure 3.7 Exit air temperature versus time_ Buckheart

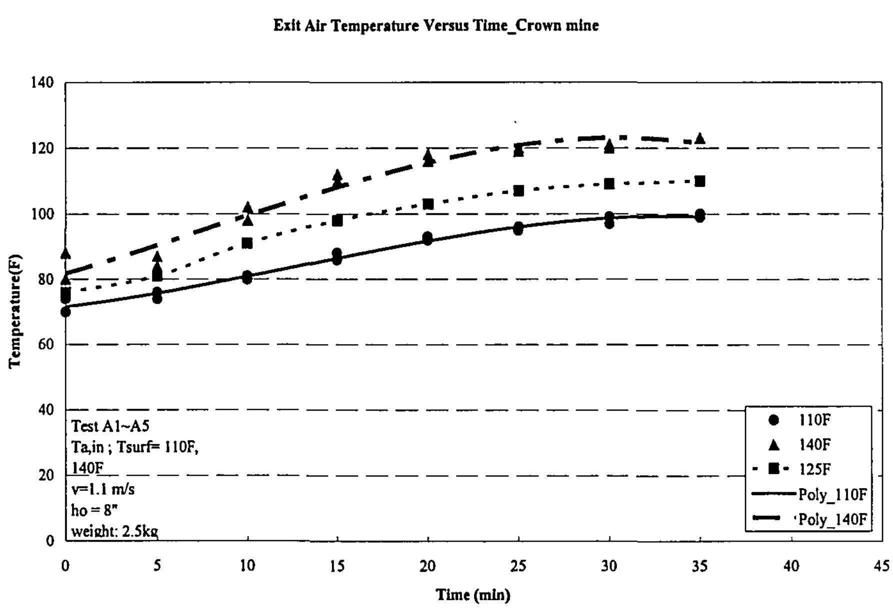

Figure 3.8 Exit air temperature versus time_ Crown mine

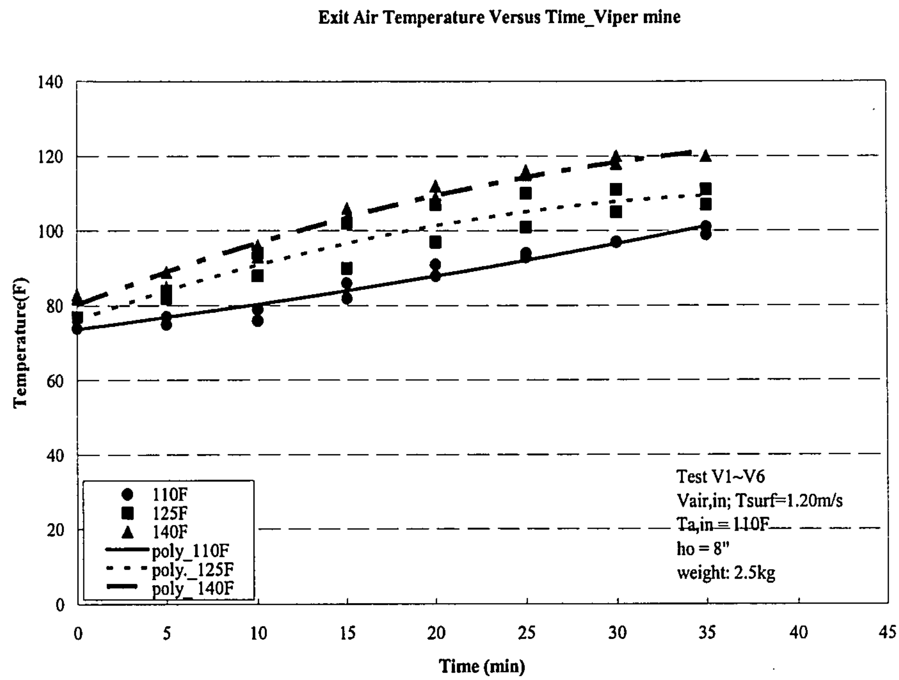

Figure 3.9 Exit air temperature versus time_ Viper mine

3.4 Exit Specific humidity

The specific humidity was obtained from (Ref. 16)

$$W = \frac{(1093 - 0.556t^{*})W_s^{*} - 0.240(t - t^{*})}{1093 + 0.444t - t^{*}} \qquad (2)$$

where $$W_s^{*} = 0.62198 \frac{p_{ws}}{p - p_{ws}} \qquad (3)$$

From the thermocouples located at the exit of the fluidized bed, the dry and wet bulb temperatures of the exit air were measured. Using Equation (2), the specific humidity of the exit air was calculated. Figure 3.10 – 3.12 indicate the variations between specific humidity and saturated air in 140°F. At the beginning, the specific humidity was close to saturated conditions. With the increase of difference between these two, the coal moisture content was decreasing.

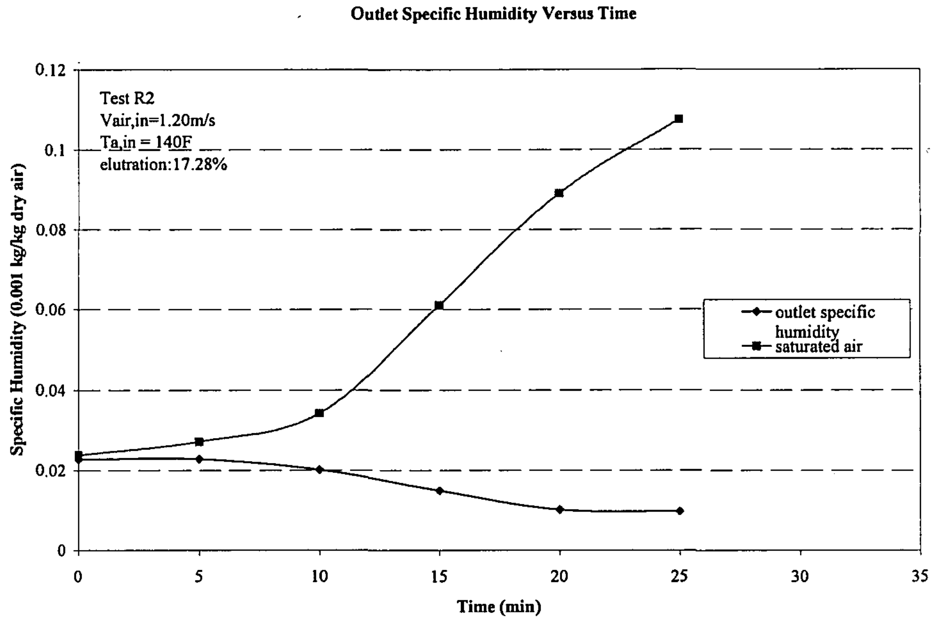

Figure 3.10 Specific humidity versus time _ Buckheart

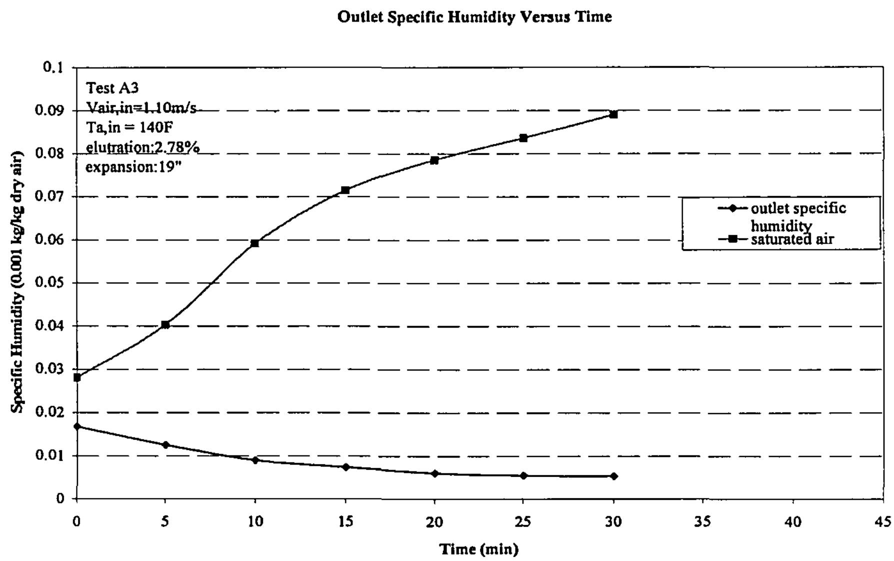

Figure 3.11 Specific humidity versus time _ Crown mine

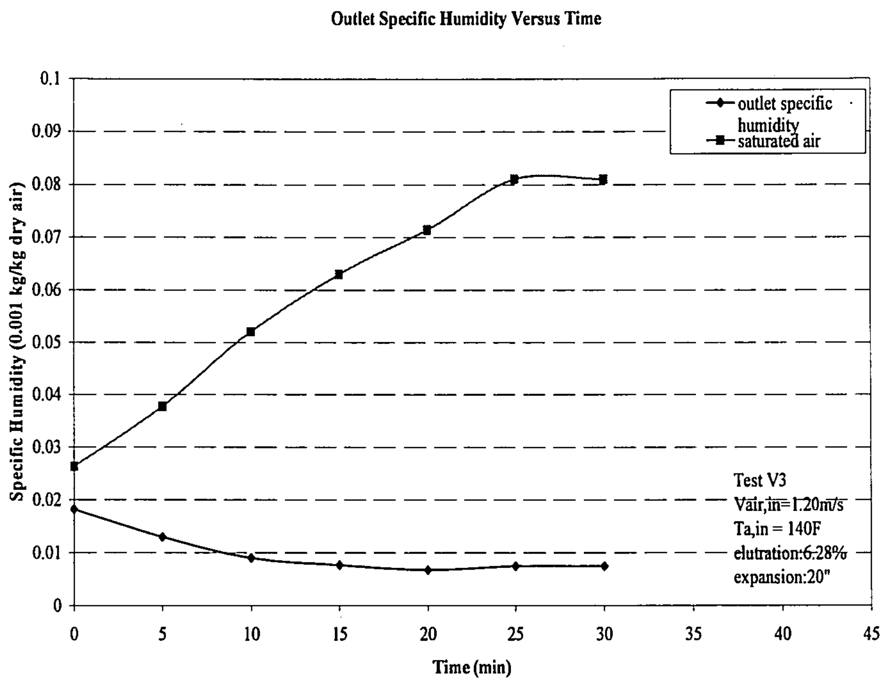

Figure 3.12 Specific humidity versus time _ Viper mine

3.5 Relative humidity

The relative humidity (ϕ) can be calculated from (Ref. 16)

$$\phi = \frac{p_w}{p_{ws}} = \frac{\mu}{1-(1-\mu)(p_{ws}/p)} \tag{4}$$

where the Degree of Saturation, μ, is

$$\mu = \left.\frac{W}{W_s}\right|_{t,p} = \frac{\phi}{1+(1-\phi)W_s/0.62198} \tag{5}$$

The relative humidity of air can also be expressed as a function of coal moisture content. Figure 3.13~3.15 show the relation between these two. The data were fitted by an exponential or polynomial function. By using these relations, along with the equations of conservation of mass and conservation of energy, the coal drying mathematical model could be developed.

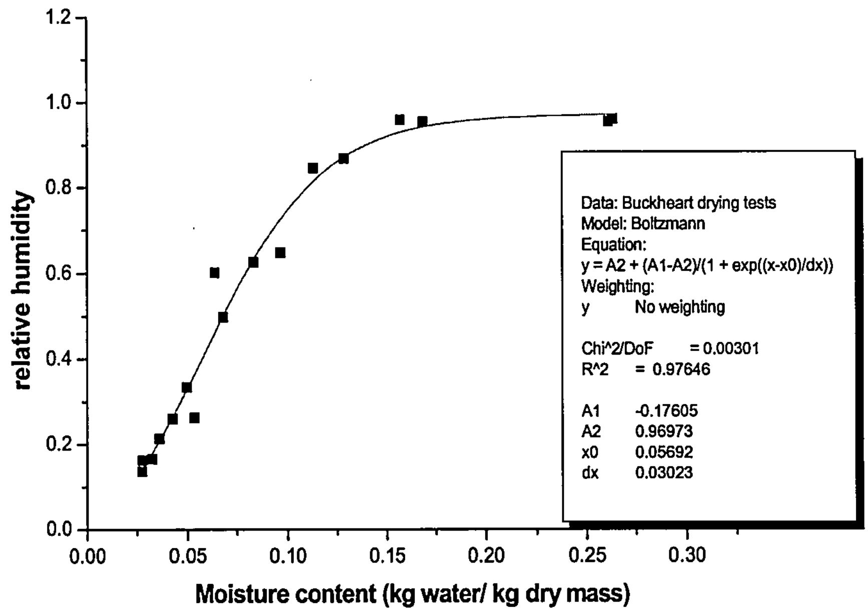

Figure 3.13 Relative humidity versus moisture content _ Buckheart

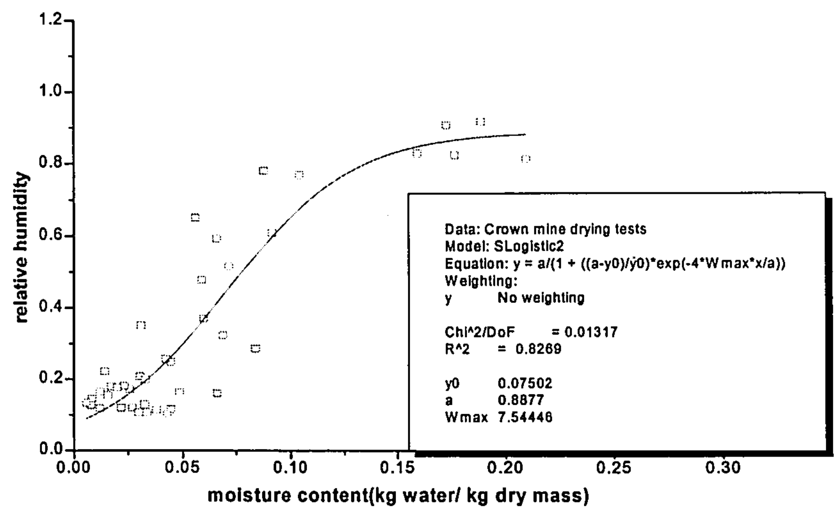

Figure 3.14 Relative humidity versus moisture content _ Crown mine

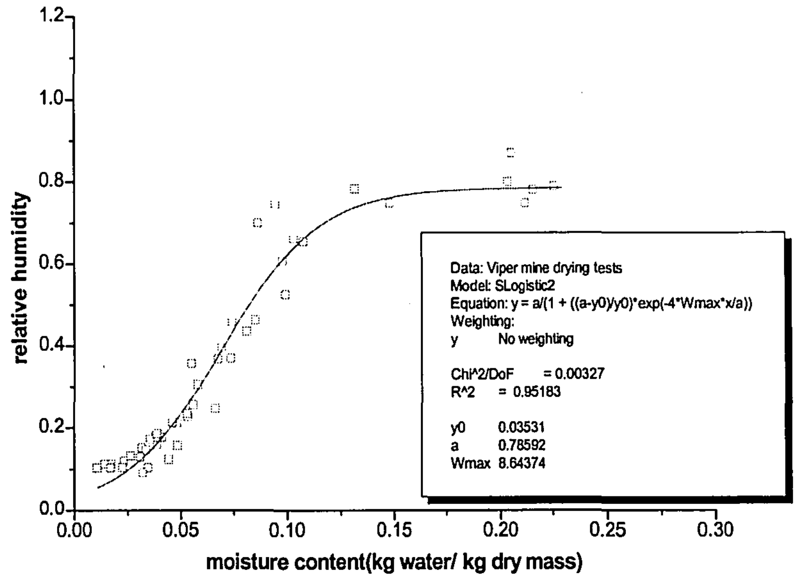

Figure 3.15 Relative humidity versus moisture content _ Viper mine

3.6 Bed and surface temperature

The surface temperature was set equal to the inlet air temperature during the test. The higher temperature the in-bed heaters have, the lower the moisture content of the coal would be. The power input of the heaters was adjusted continuously to keep the surface temperature stable. Figures 3.16 - 3.18 show the bed, surface and exit temperatures. The bed temperatures measured by the top and bottom thermocouples are very consistent. That means the coal in the bed is well fluidized and mixed. Also, with the increase of the difference between dry and wet bulb temperature at the exit of our system, the coal moisture content was simultaneously reduced.

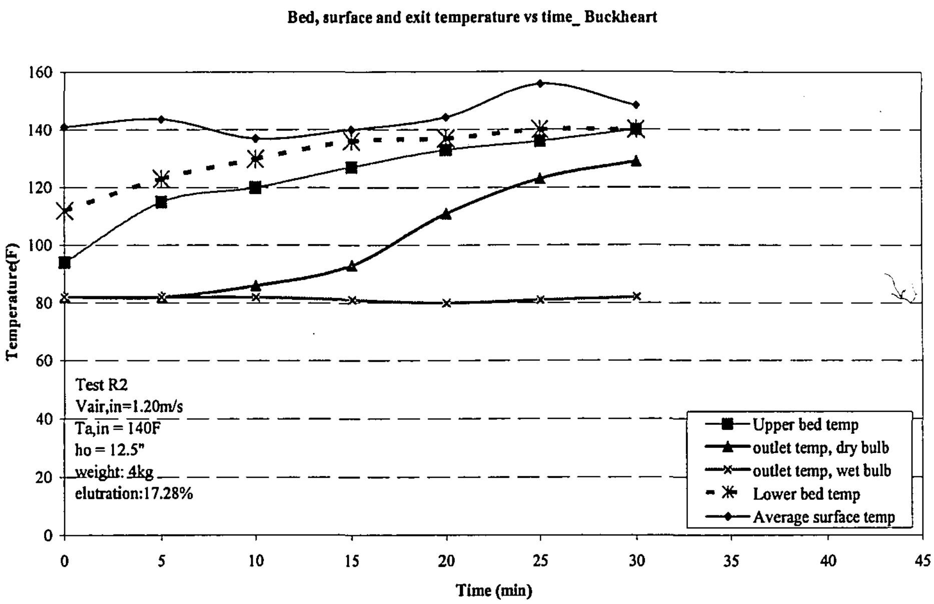

Figure 3.16 Bed, surface and exit temperature versus time_ Buckheart

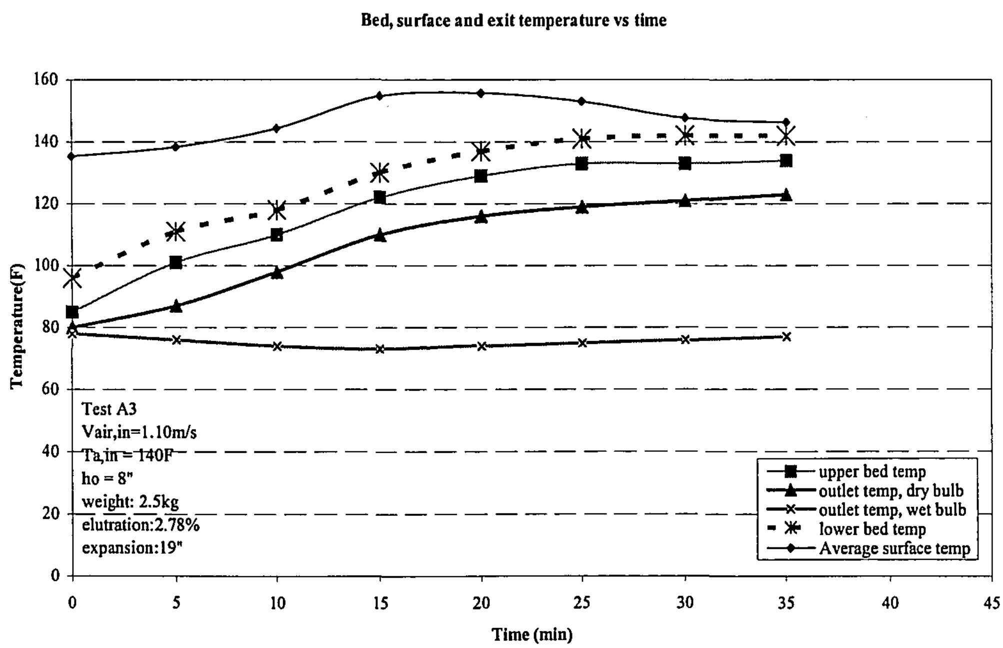

Figure 3.17 Bed, surface and exit temperature versus time_ Crown mine

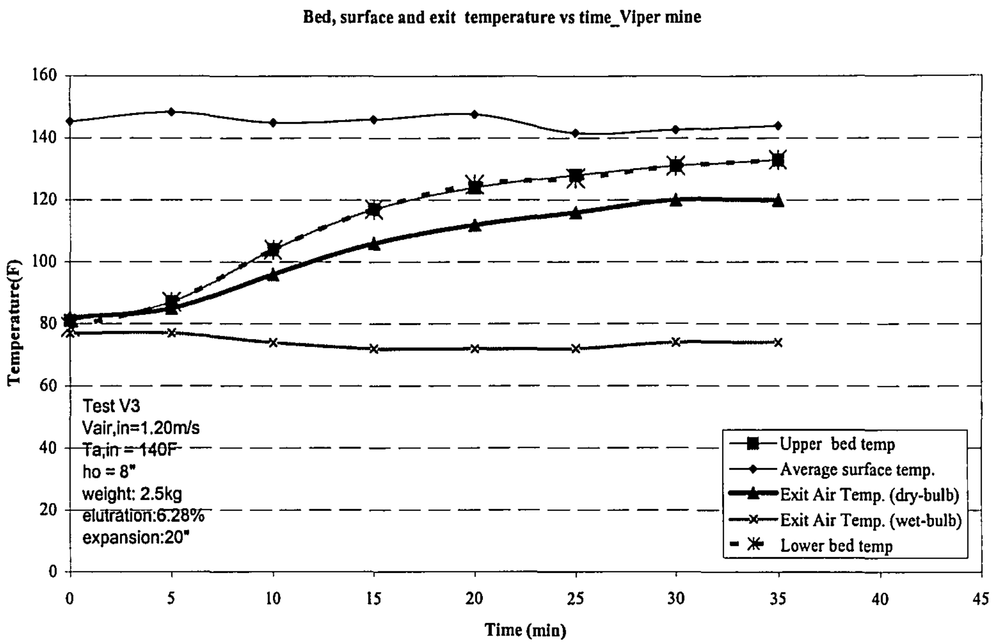

Figure 3.18 Bed, surface and exit temperature versus time_ Viper mine

3.7 Heat transfer coefficient

The heat loss in our system is considered relatively low and was neglected. The heat transfer coefficient of in-bed heaters can be expressed as (Ref. 17)

$$h = \frac{\dot{Q}_{heater}}{A_h(T_{heater} - T_{bed})} \tag{6}$$

It can be seen in Fig3.19 that the heat transfer coefficients are lower for wet materials and increase slightly during the drying process.

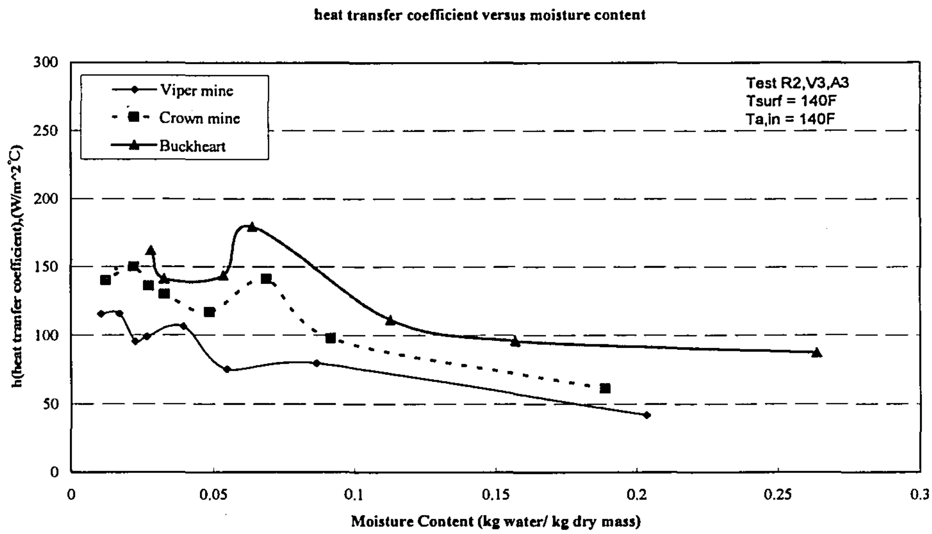

Figure 3.19 the heat transfer coefficients versus moisture content

3.8 Type of coal

Experiments were performed with the Crown mine and Viper mine coals at comparable test conditions to determine the relative rates of drying of these two fuels. Tests were also run to determine if the key parameters have the same effect on the drying kinetics for different kinds of coals. Fig 3.20 ~ 3.22 show the drying curves for the two coals in 110°F, 125°F and 140°F. These tests were done with the same values of coal top size, settled bed depth, air and heater temperature, and approximately the same air velocity. The drying rate for these coals was shown in Fig 3.23. In the first 5 minutes, the drying rate of Viper mine was higher than Crown mine by 28% in 140°F, by 36% in 125°F and by 13% in 110°F. Obviously, there was only small difference between these two coals in

110°F. The exit air temperature was also considered in the tests. Fig 3.24 and 3.25 compare the exhaust air temperature for these two coals in different drying temperature. The values for Viper mine and Crown mine were almost the same during the drying tests, and the trends for those two coals were similar to Lignite (Ref. 18). When considering the time requirements to reduce 80% moisture content, as shown in Fig 3.26 and 3.27, the Crown mine coal has a better drying performance than the Viper mine coal. For the Buckheart and Viper mine coal, the time required to reach 80% moisture reduction was decreased when using higher drying temperature.

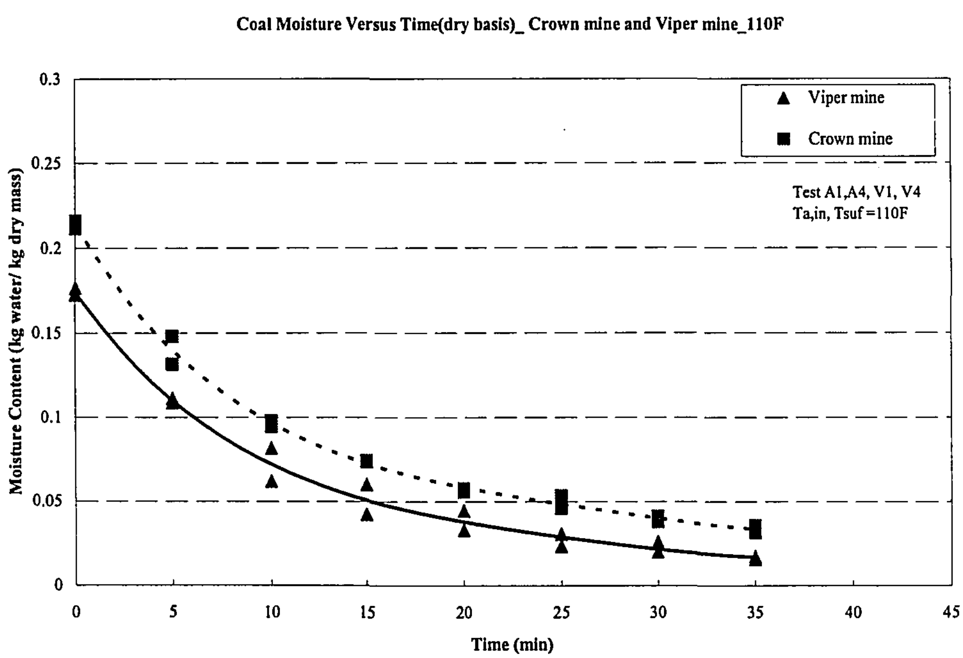

Figure 3.20 Drying Curve at low temperauture_110°F

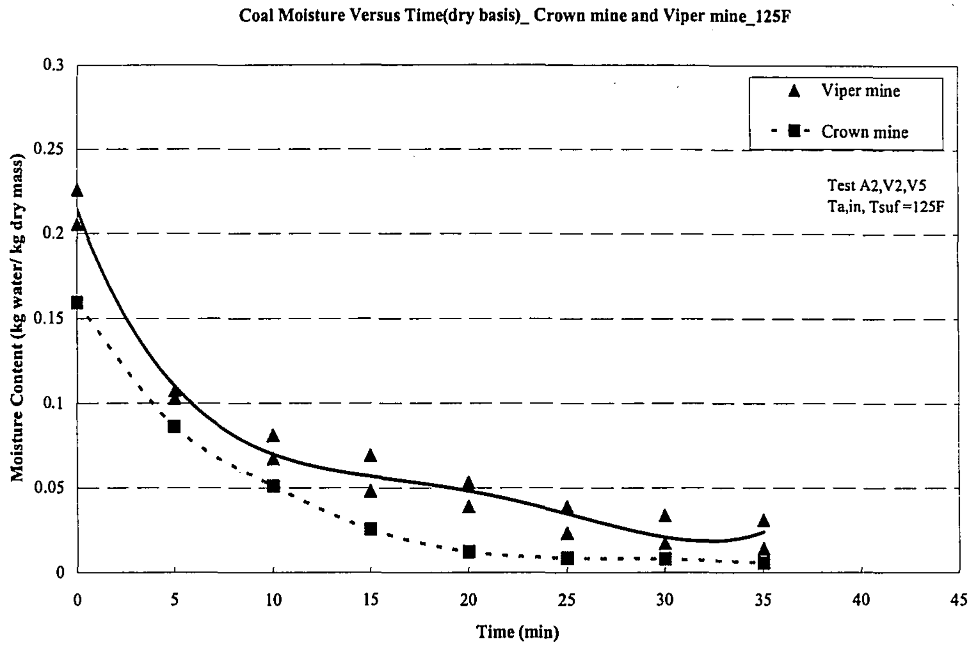

Figure 3.21 Drying Curve at low temperauture_125°F

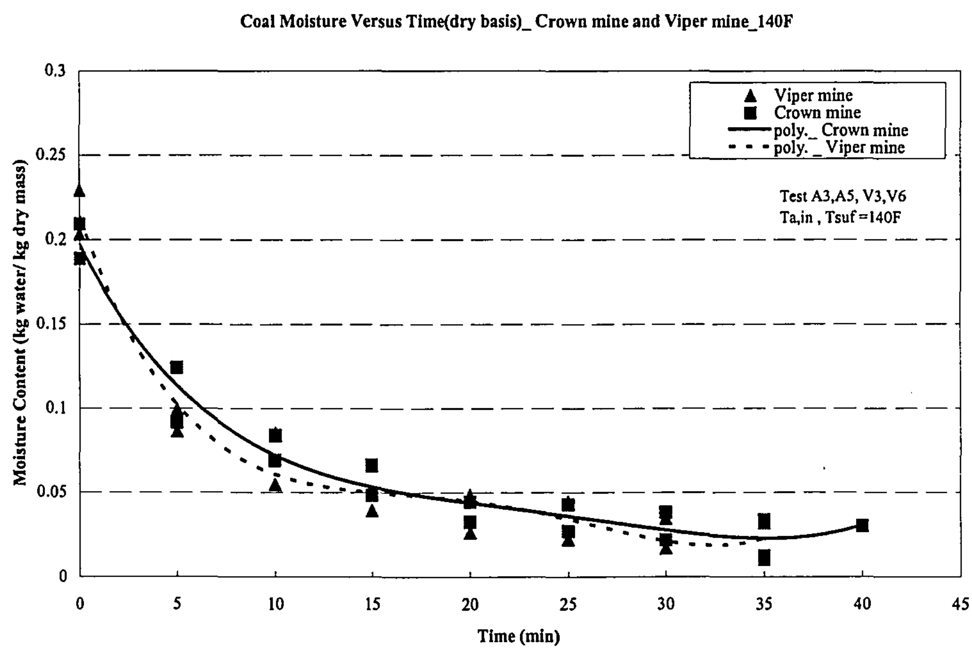

Figure 3.22 Drying Curve at high temperature_140°F

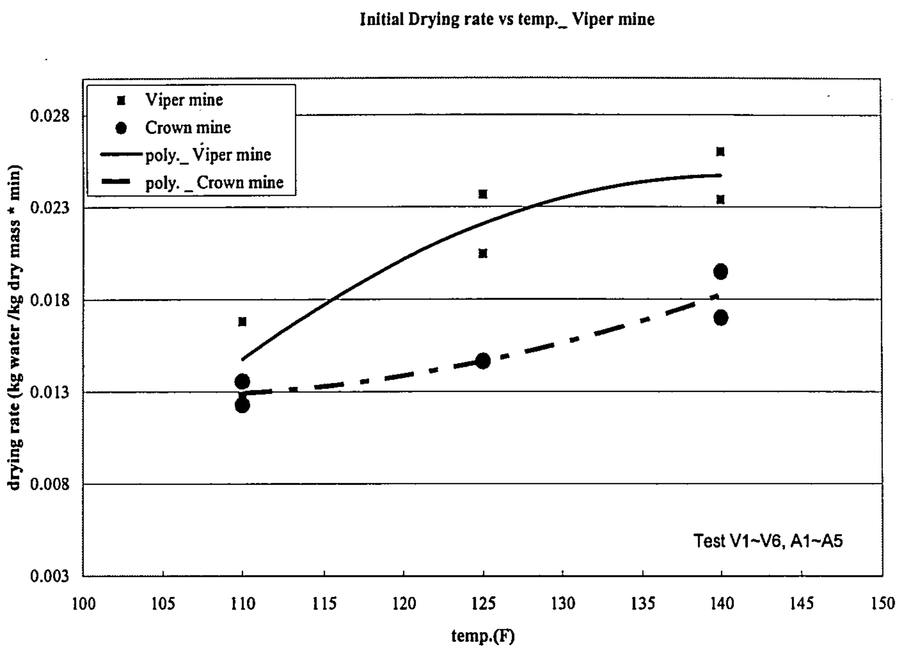

Figure 3.23 Drying Rate versus temperature

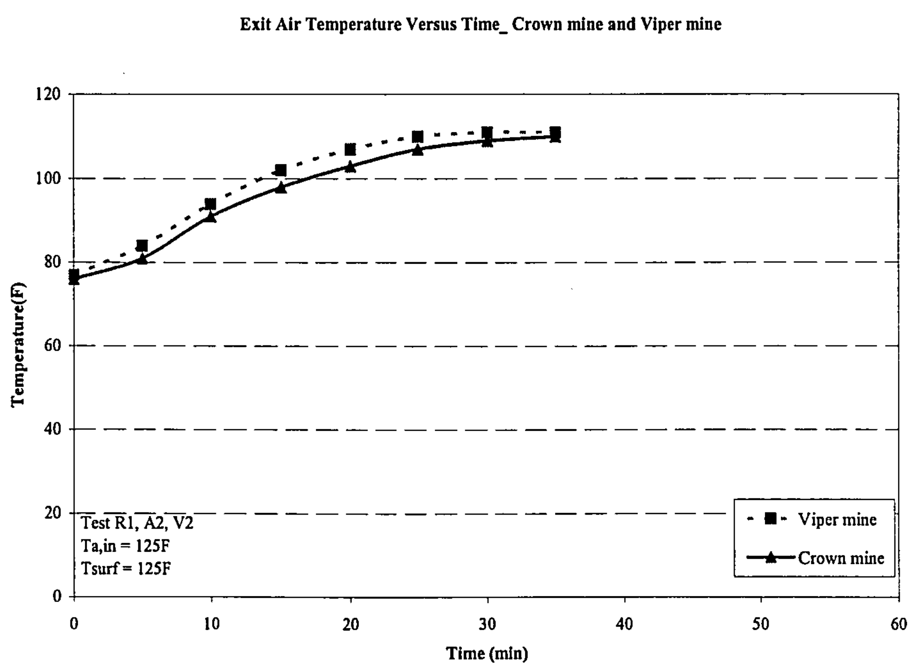

Figure 3.24 Exit air temperature versus time in 125°F

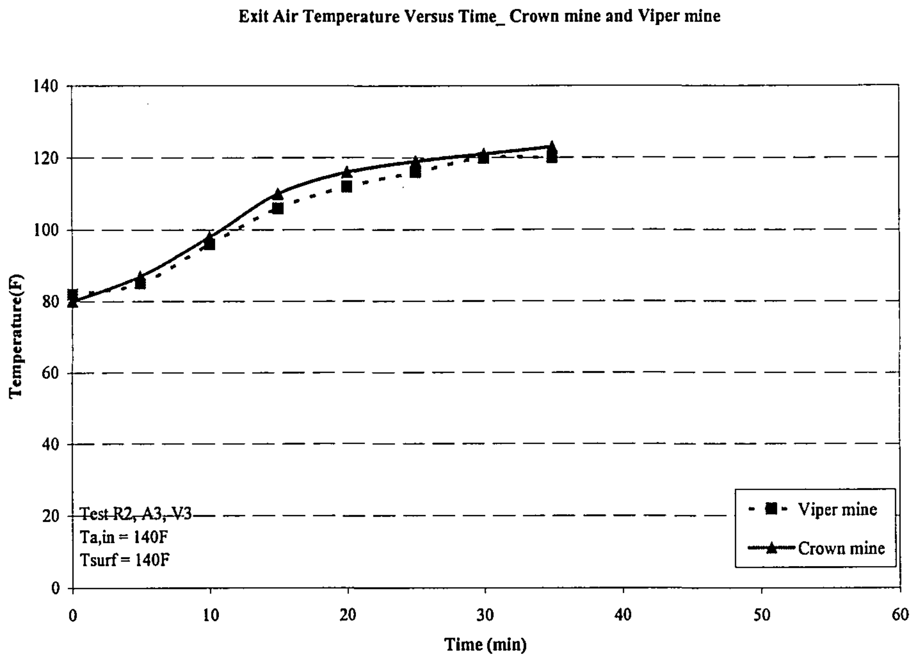

Figure 3.25 Exit air temperature versus time in 140°F

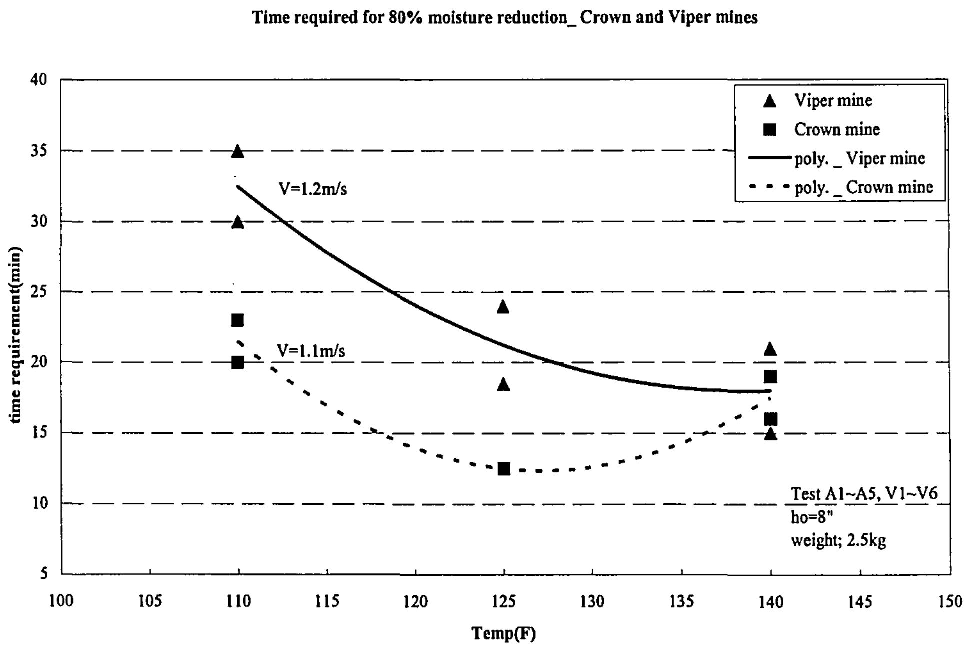

Figure 3.26 Time required for 80% moisture reduction _
The Crown and Viper mine coals

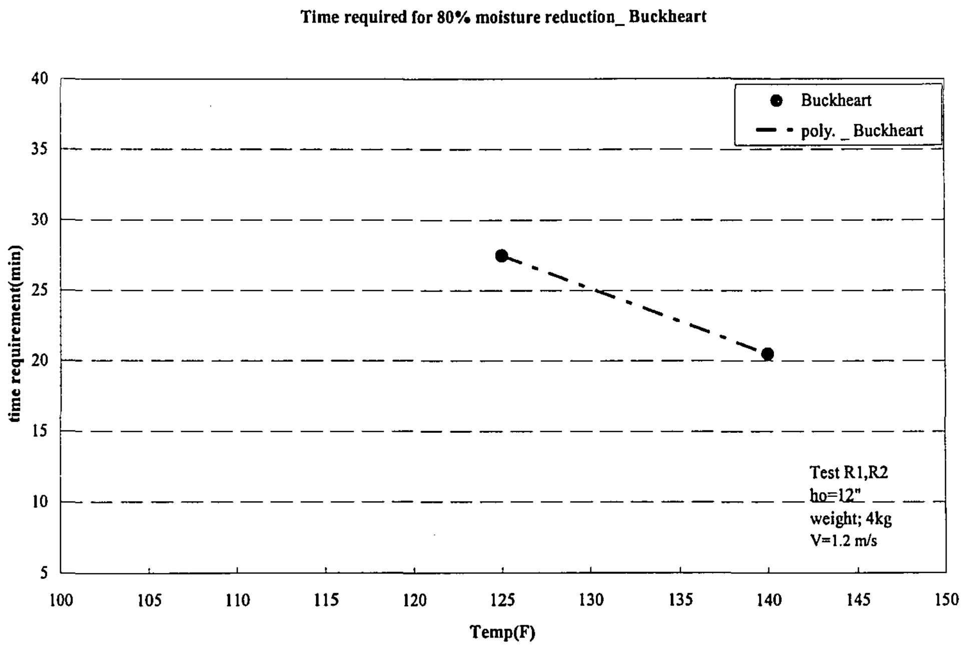

Figure 3.27 Time required for 80% moisture reduction _ Buckheart

Chapter 4 Theoretical model

The laboratory data in this study were obtained with various drying conditions as shown in the previous chapter. When the drying operations are known, drying performance can be predicted by a mathematical model originally developed by Feng Gu (Ref. 18). This model was developed based on the comprehensive understanding of the mechanisms of drying process.

The parameters controlled in this simulation were inlet air velocity, inlet air temperature, in-bed heater temperature, specific humidity, initial moisture and mass of dry coal. The four parameters which were calculated as a function of time, are coal moisture content (Γ), exit air temperature (T_2), exit air specific humidity (ω_2) and exit air relative humidity (φ_2). The control volume is sketched in Fig 4.1.

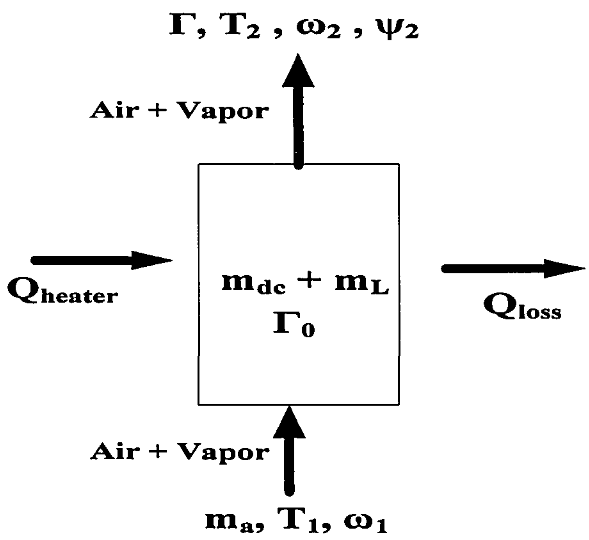

Fig 4.1 Sketch of control volume

To describe the drying process, several assumptions were made: (a) at any instant of time , the particles and air in the bed are at the same temperature (b) gas and particle properties do not vary with vertical distance in the bed (c) the temperature, flowrate and specific humidity of inlet air remain constant during a test (d) the energy losses on the dryer wall only occur in the interstitial gas phase (e) the solid phase behaves as a perfect mixer (f) all the transfer mechanisms presented in the bubble gas phase are purely convective and unidirectional (g) the mass of inlet and outlet dry air are equal, while the water vapor content increases as the air passes through the dryer.

The governing equations for the drying process can be written as follows:

(1) Conservation of energy (Ref. 5, Ref. 18):

$$Q_{heater} - Q_{loss} = \frac{d(m_{dc}u_{dc})}{dt} + \frac{d(m_L u_L)}{dt} + (m_a h_a + m_v h_v)_2 - (m_a h_a + m_v h_v)_1$$
$$= m_{dc}[(C_c + \Gamma C_L)\frac{dT_2}{dt} + u_L(-\frac{\dot{m}_a}{m_{dc}})(\omega_2 - \omega_1)] + \dot{m}_a[C_{pa}(T_2 - T_1) + \omega_2 h_{g2} - \omega_1 h_{g1}] \tag{7}$$

The left term is heat flux transferred through the system. The term $\frac{d(m_{dc}u_{dc})}{dt} + \frac{d(m_L u_L)}{dt}$ represents internal energy change in the control volume, and $(m_a h_a + m_v h_v)_2 - (m_a h_a + m_v h_v)_1$ represents enthalpy change during the drying test. The equation of enthalpy can be obtained by data curve fitting of Thermodynamic properties table. It can be written as:

$$h_g = -6E\text{-}07\times T^3 + 6E\text{-}05\times T^2 + 0.4369\times T + 1061.4 \qquad (8)$$

(2) Conservation of mass (Ref. 5):

$$m_{dc}.\frac{d\Gamma}{dt} + m_a.(\omega_2 - \omega_1) = 0 \qquad (9)$$

$$\text{Where } \Gamma = \frac{m_L}{m_{dc}} \qquad (10)$$

(3) Equation of specific humidity and relative humidity (Ref. 16)

$$\omega_2 = \frac{0.622\times\phi_2\times P_{g2}}{P-\phi_2\times P_{g2}} \qquad (11)$$

The saturation pressure (P_{g2}) can be defined by the curve fitting of data from Thermodynamic properties table. The equation of saturation pressure is:

$$P_{g2} = 5E\text{-}06\times T^3 - 0.0011\times T^2 + 0.0999\times T - 2.5654 \qquad (12)$$

(4) Equation of relative humidity and coal moisture content

The relation between coal moisture content and relative humidity of air leaving the bed $\phi = f(\Gamma)$ is given graphically in Fig 4.2~4.3 for the Buckheart, Fig 4.4~4.5 for the Crown mine and Fig 4.6~4.7 for the Viper mine coals. By curve fitting of these data, the equations of relative humidity versus coal moisture content can be acquired.

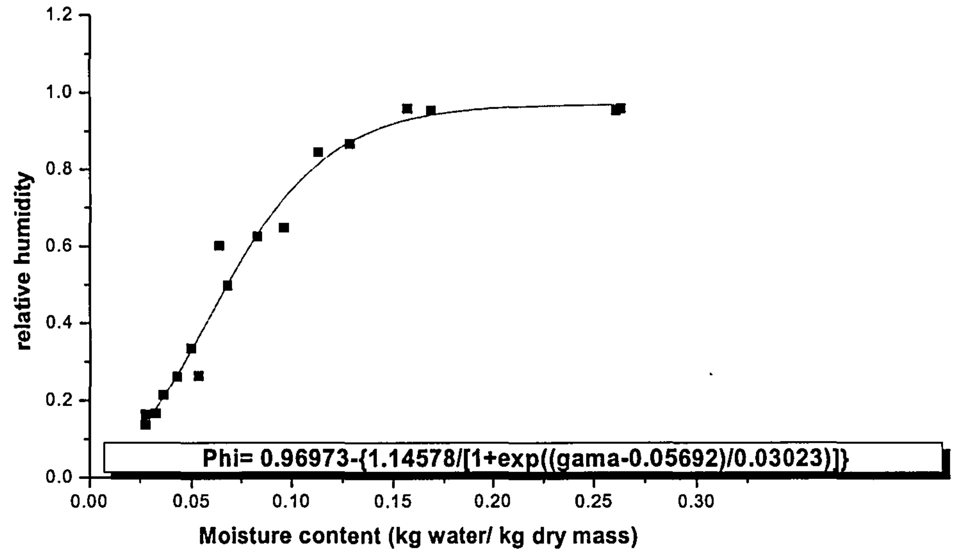

Fig 4.2 Relative humidity versus coal moisture content_ Buckheart _ Exponential function

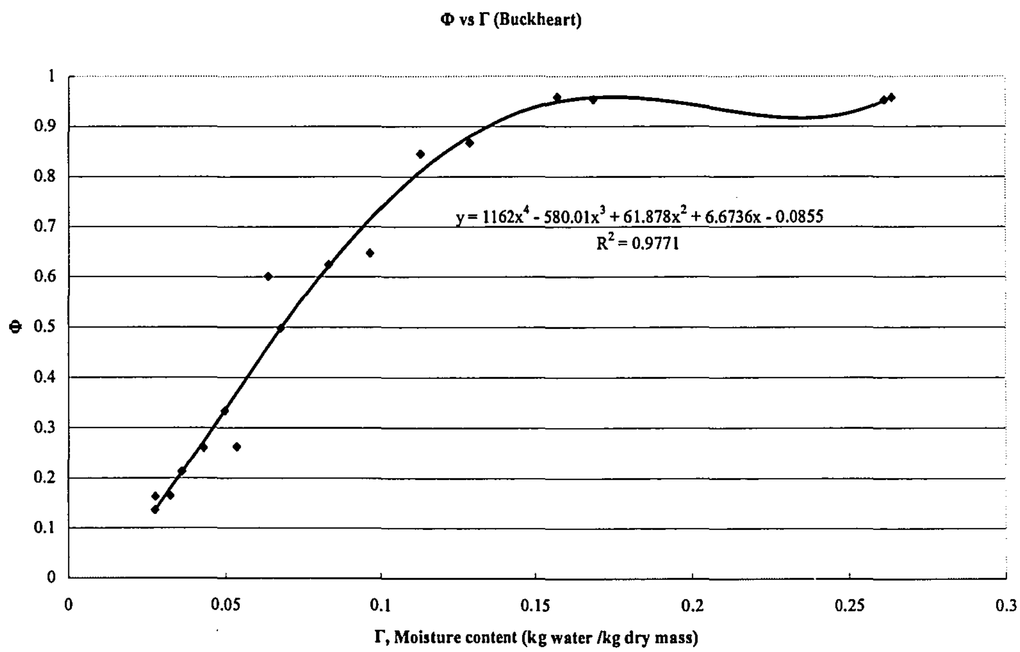

Fig 4.3 Relative humidity versus coal moisture content_ Buckheart _ Polynomial function

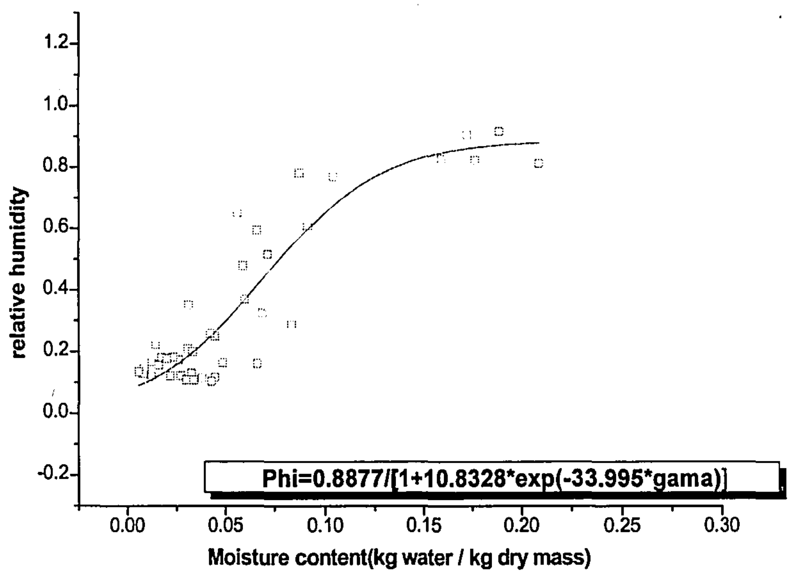

Fig 4.4 Relative humidity versus coal moisture content_ Crown mine _ Exponential function

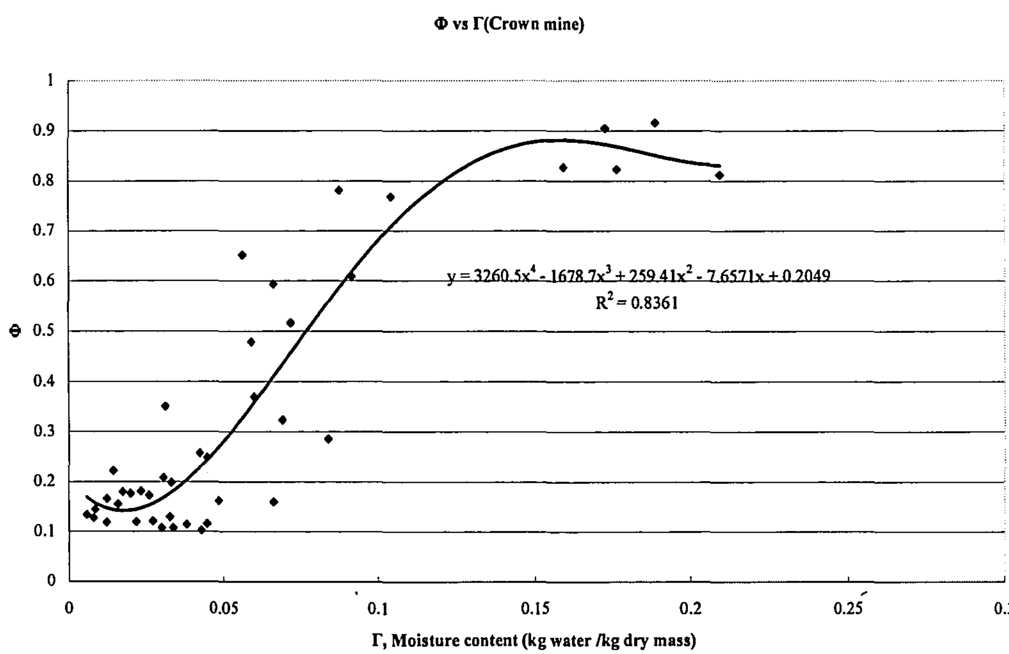

Fig 4.5 Relative humidity versus coal moisture content_ Crown mine _ Polynomial function

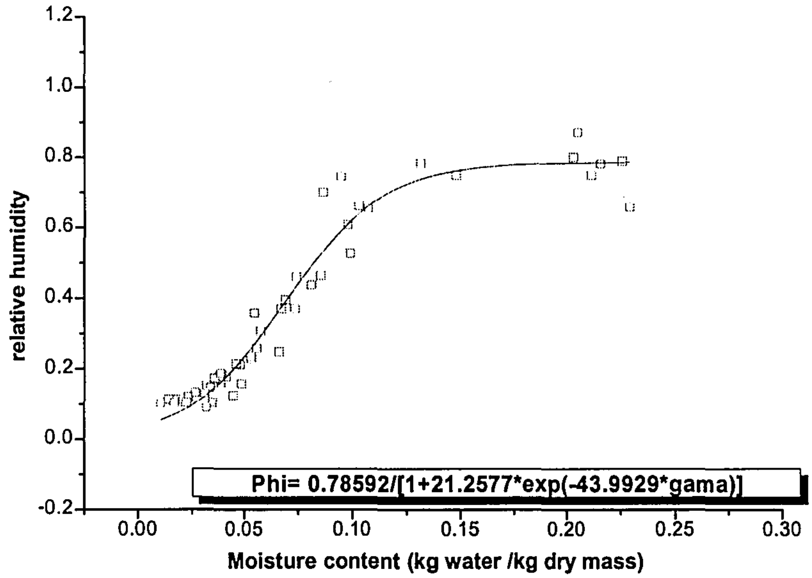

Fig 4.6 Relative humidity versus coal moisture content_ Viper mine _ Exponential function

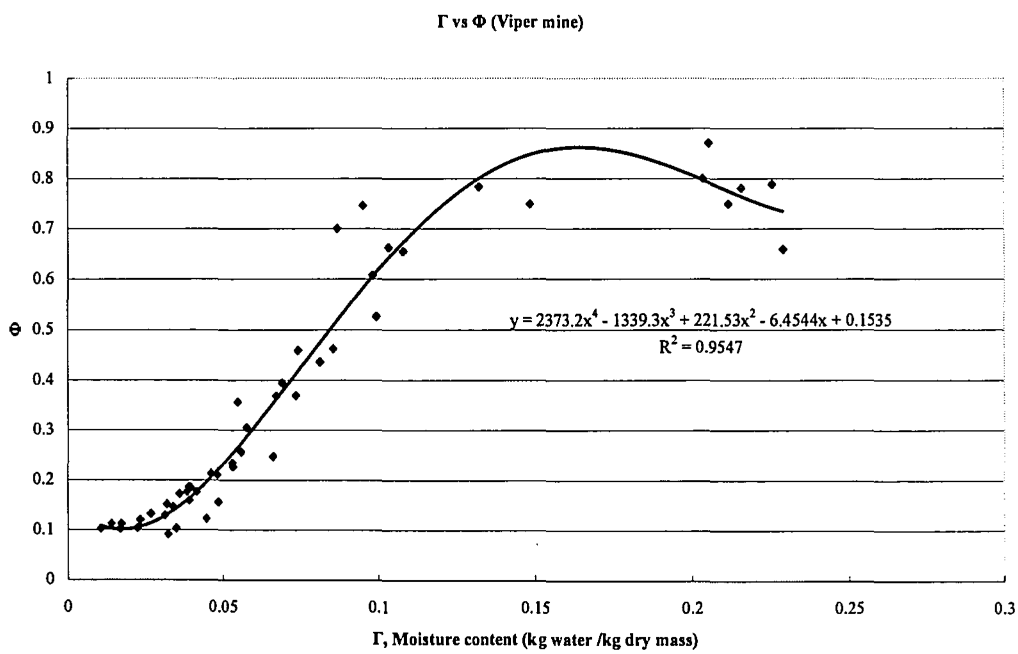

Fig 4.7 Relative humidity versus coal moisture content_ Viper mine _ Polynomial function

Two equations, exponential and polynomial functions, were developed from these relations. For Buckheart, the equation is

$$\phi = 0.96973 - \frac{1.14578}{1 + \exp(\frac{\Gamma - 0.05692}{0.03023})} \tag{13}$$

or $$\phi = 1162{*}\Gamma^4 - 580.01{*}\Gamma^3 + 61.878{*}\Gamma^2 + 6.6736{*}\Gamma - 0.0855 \tag{14}$$

For Crown mine, the equation is

$$\phi = \frac{0.8877}{1 + 10.8328 \times \exp(-33.995\Gamma)} \tag{15}$$

or $$\phi = 3260.5{*}\Gamma^4 - 1678.7{*}\Gamma^3 + 259.41{*}\Gamma^2 - 7.6571{*}\Gamma + 0.2049$$

For Viper mine, the equation is

$$\phi = \frac{0.78592}{1 + 21.2577 \times \exp(-43.9929\Gamma)} \tag{16}$$

or $$\phi = 2373.2{*}\Gamma^4 - 1339.3{*}\Gamma^3 + 221.53{*}\Gamma^2 - 6.4544{*}\Gamma + 0.1535 \tag{17}$$

The equations of energy balance, mass balance, the relation of specific and relative humidity, as well as the relation of relative humidity and coal moisture content were used to calculate the four unknowns, which are coal moisture content during drying tests (Γ), exit air temperature (T_2), exit specific humidity (ω_2), and exit relative humidity (ϕ). The initial coal moisture content was used to obtain relative humidity by equation (13) ~ (15). Through equation (11), exit specific humidity can be acquired. Equation (7) and (9) were used to calculate the changing rate of exit air temperature and moisture content. After knowing these two values, the numerical method was applied to calculate the following coal moisture content and exit air temperature. This equilibrium model can be compared with the experimental results to see how the prediction works.

Chapter 5 Simulation results compared with measured values

Some cases were run numerically from the experimental conditions and compared with the experimental results. Four parameters, which are moisture content, exit air temperature, exit specific humidity and exit relative humidity, were performed to represent the predicted drying test results for the Buckheart, Crown mine and Viper mine coals. The two equations, exponential and polynomial functions, were compared with the same conditions in order to determine the most accurate equation.

5.1 Coal moisture content versus time

Fig 5.1 and 5.2 show the comparison of moisture content between calculation and experimental results for the Crown mine and Viper mine coals in 110°F. Lines and data points represent the calculated values and experimental results, respectively. It can be seen that these two coals present good agreement in lower temperature. When the drying temperature was increased to 125°F, as shown in Fig 5.3~5.5, there was a small difference between these two results in the first 5 minutes. Fig 5.6~5.8 give the predictions for these three coals in 140°F. The error between test and calculation results was slightly enhanced. The simulation data predict more nicely in lower temperature than in higher temperature. From the following graphs, it can be seen that using exponential functions to predict the drying performance will be better than using polynomial functions.

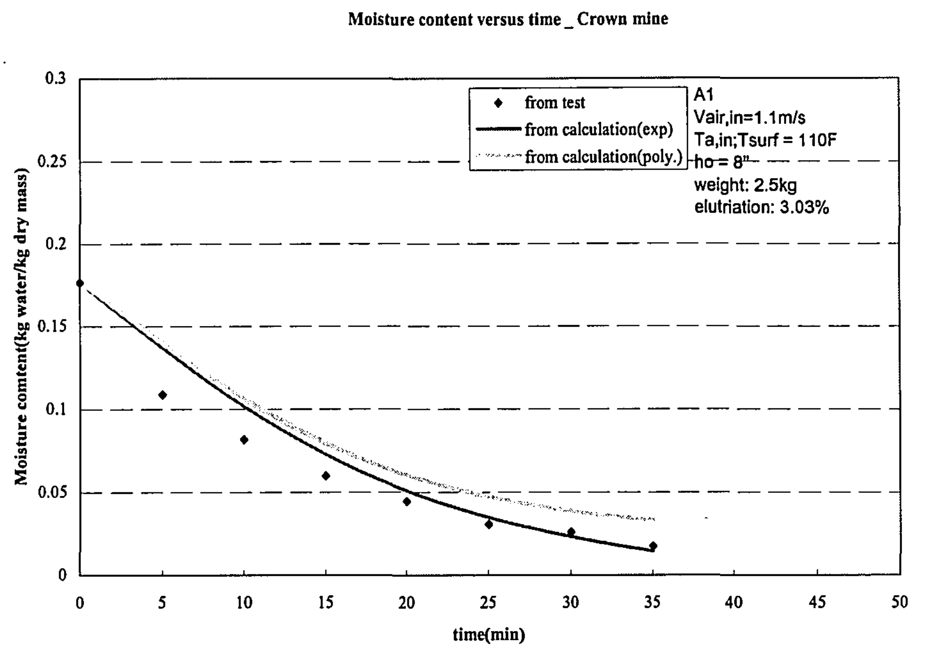

Fig 5.1 Coal moisture content prediction results _ Crown mine (110°F)

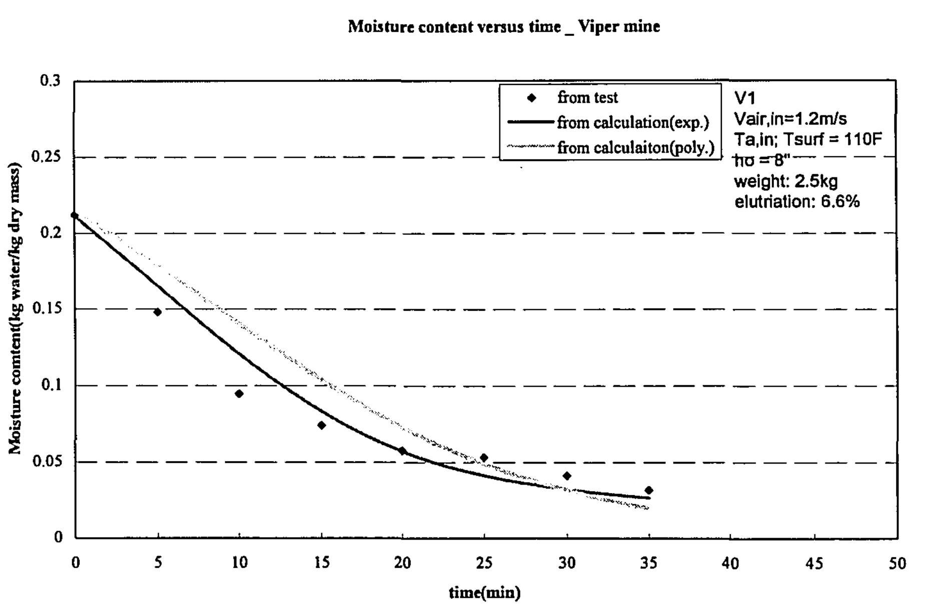

Fig 5.2 Coal moisture content prediction results _ Viper mine (110°F)

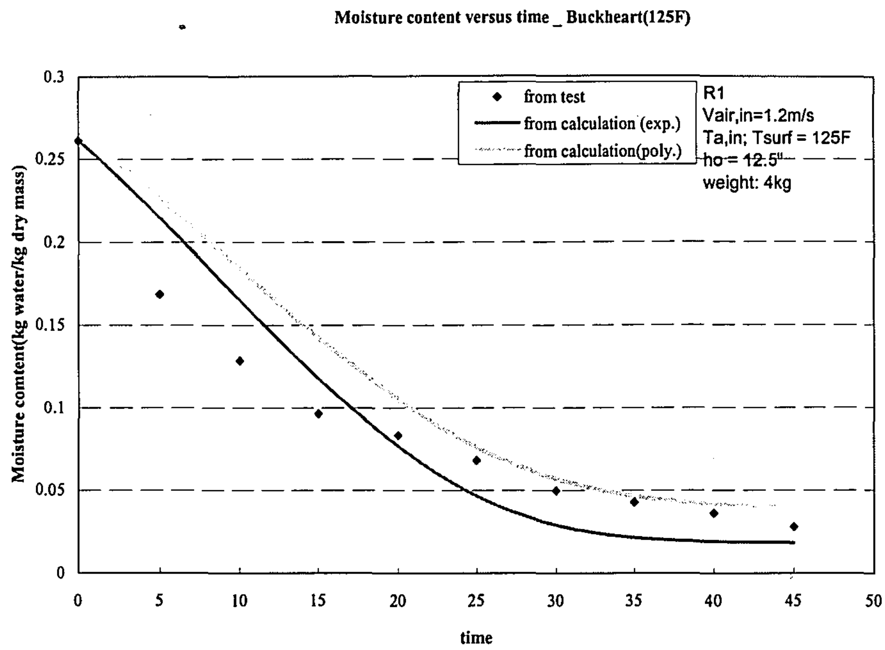

Fig 5.3 Coal moisture content prediction results _ Buckheart (125°F)

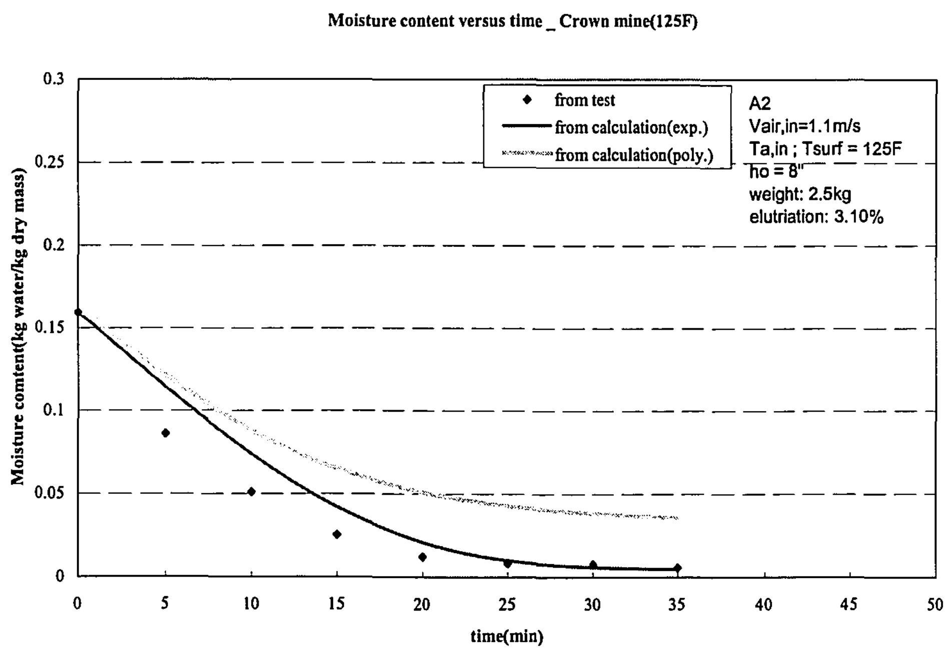

Fig 5.4 Coal moisture content prediction results _ Crown mine (125°F)

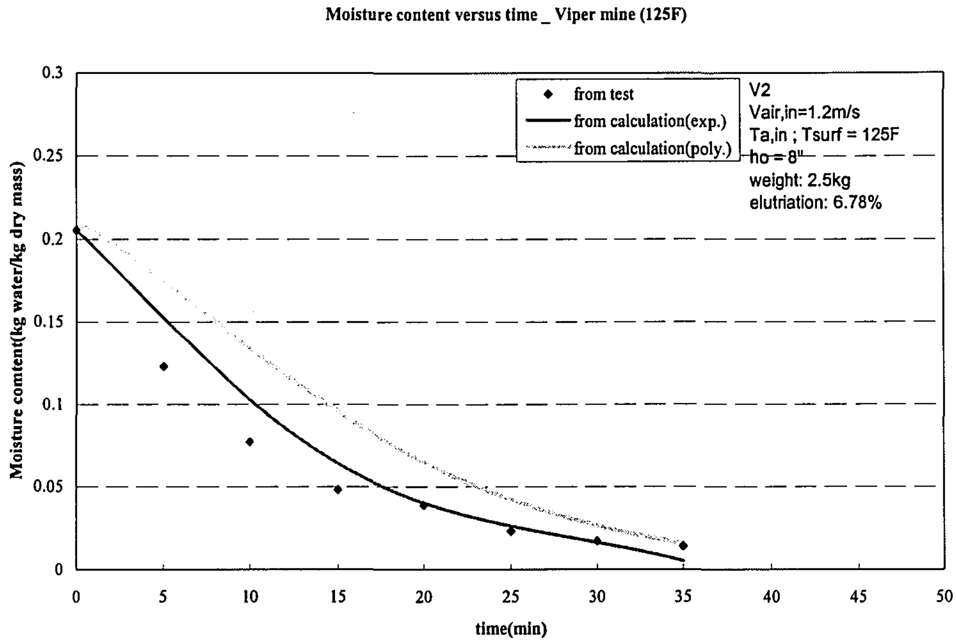

Fig 5.5 Coal moisture content prediction results _ Viper mine (125°F)

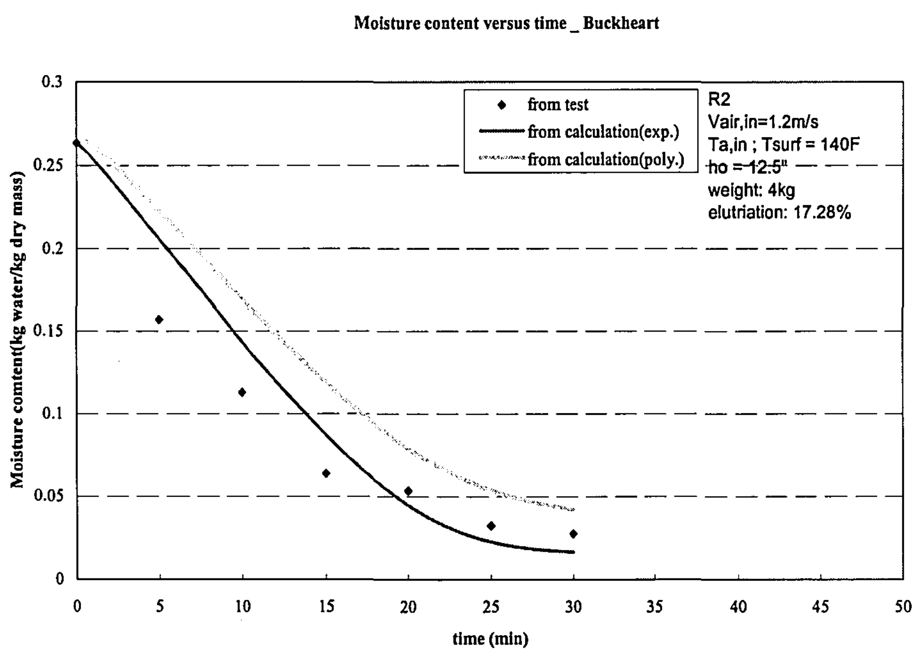

Fig 5.6 Coal moisture content prediction results _ Buckheart (140°F)

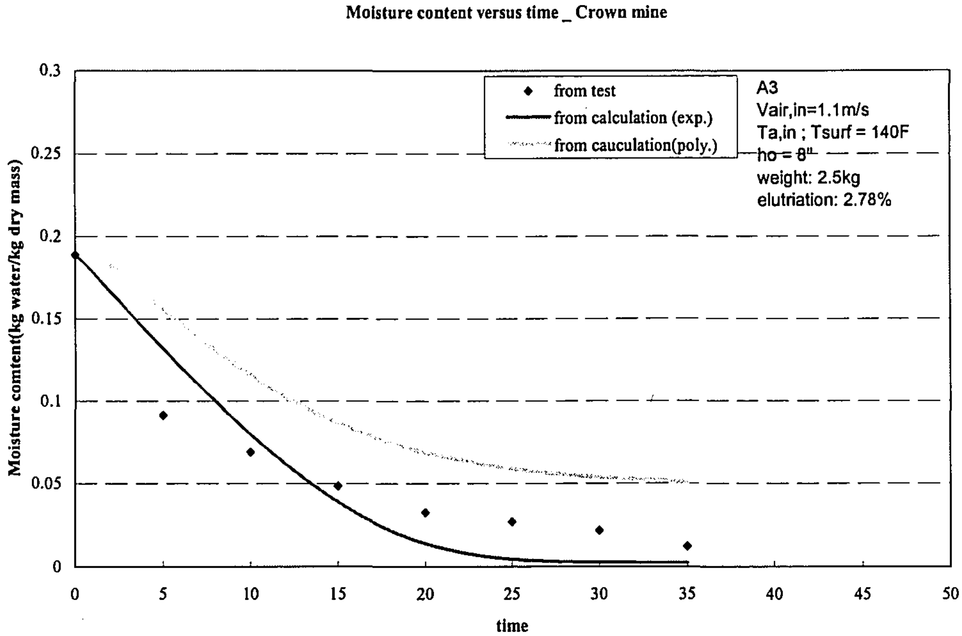

Fig 5.7 Coal moisture content prediction results _ Crown mine (140°F)

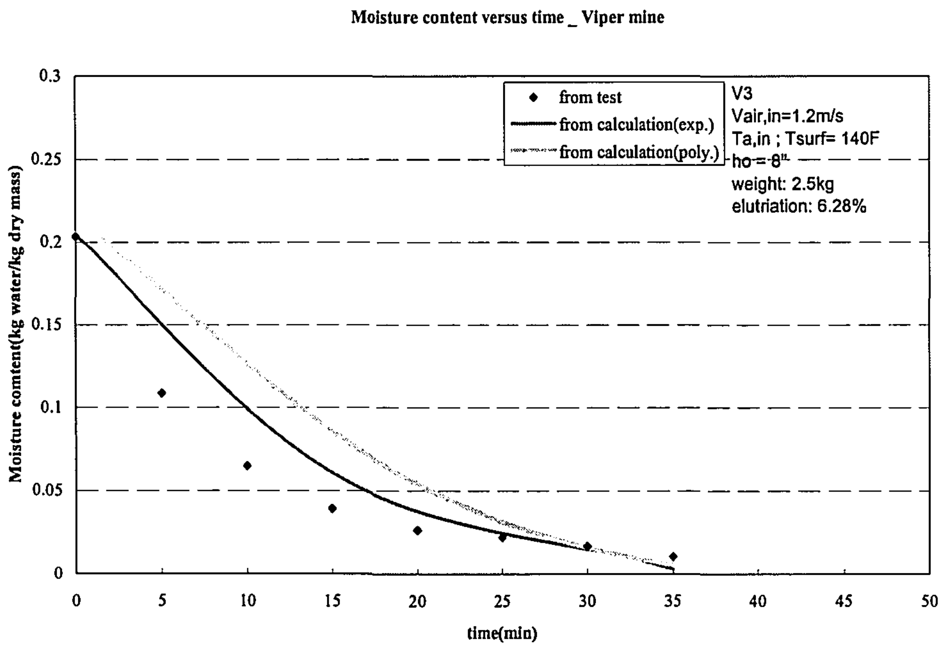

Fig 5.8 Coal moisture content prediction results _Viper mine (140°F)

5.2 Exit air temperature versus time

Comparisons between test and simulation results for exit air temperature were shown in Fig 5.9 ~ 5.16. They have nice fit, especially the Crown mine, if all the operating conditions were used to calculate drying performance.

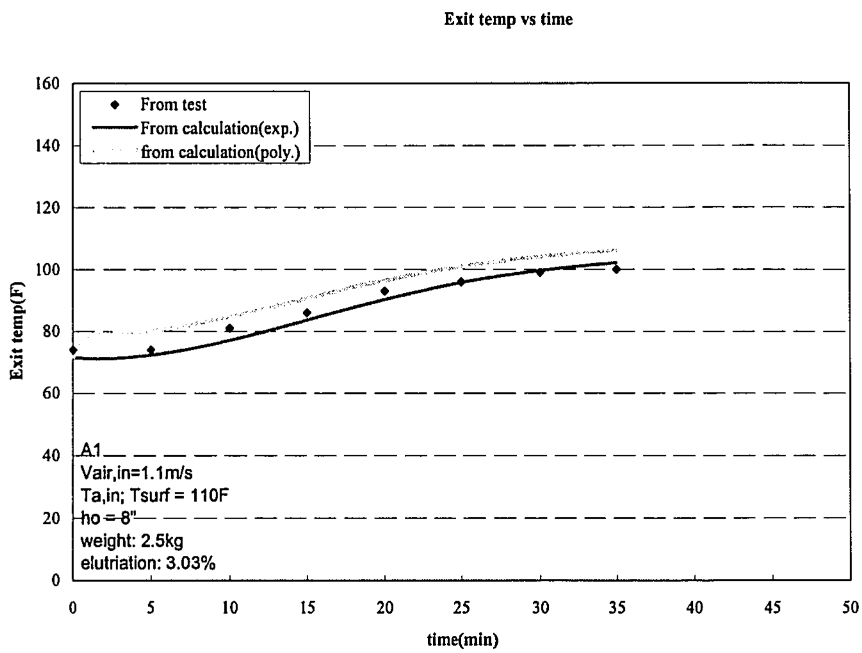

Fig 5.9 Exit air temperature simulation results _ Crown mine (110°F)

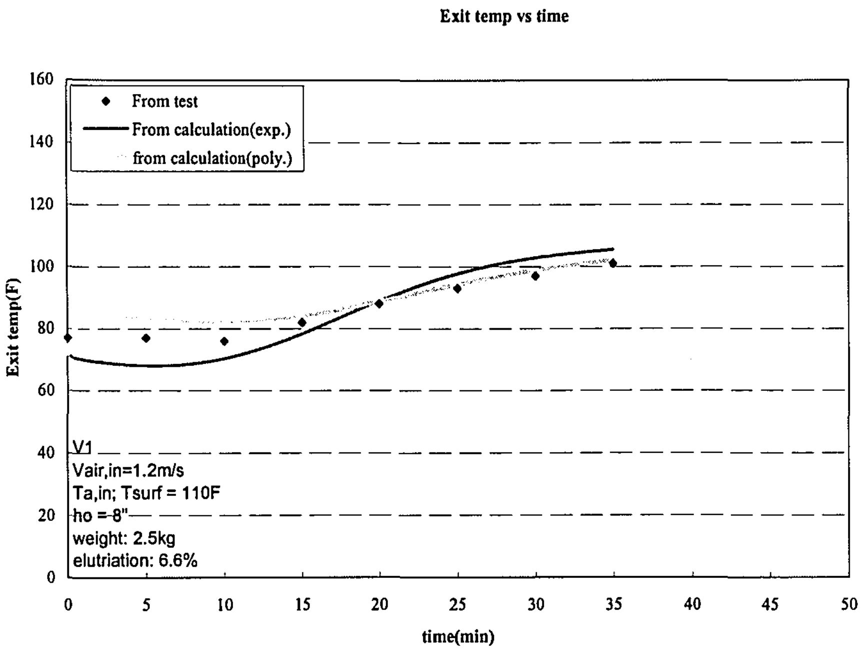

Fig 5.10 Exit air temperature simulation results _ Viper mine (110°F)

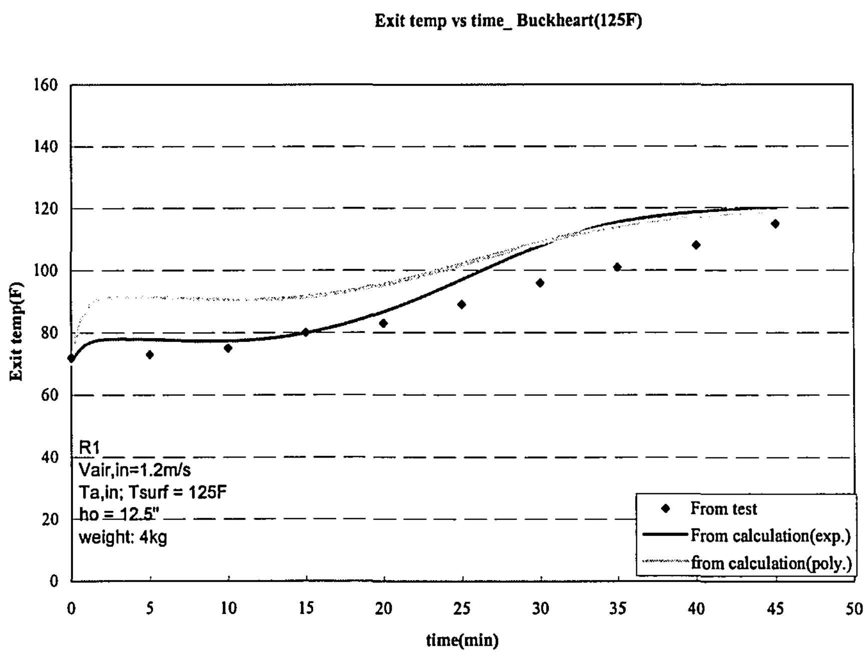

Fig 5.11 Exit air temperature simulation results _ Buckheart (125°F)

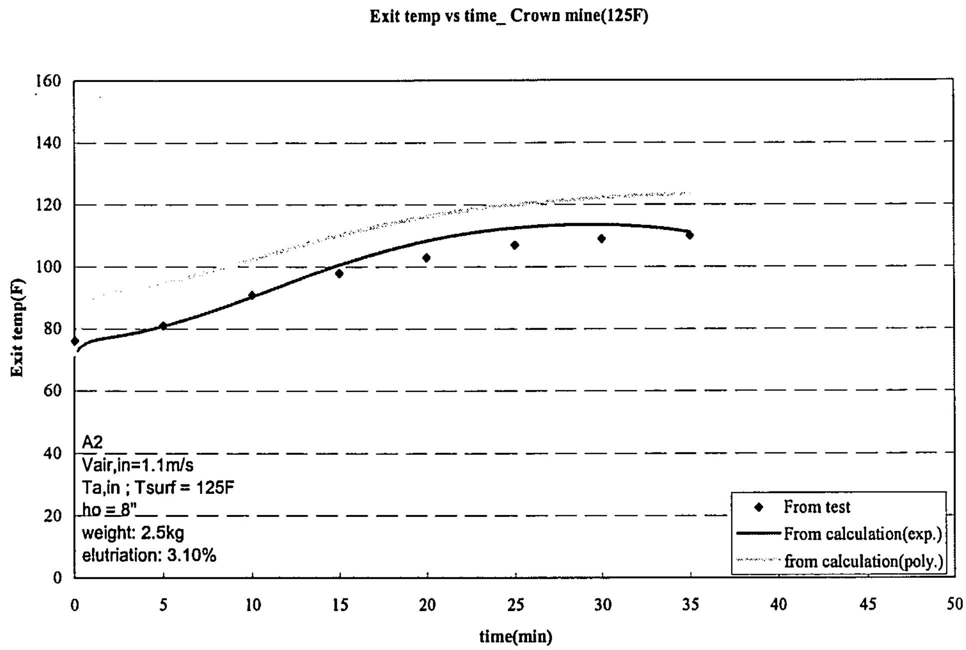

Fig 5.12 Exit air temperature simulation results _ Crown mine (125°F)

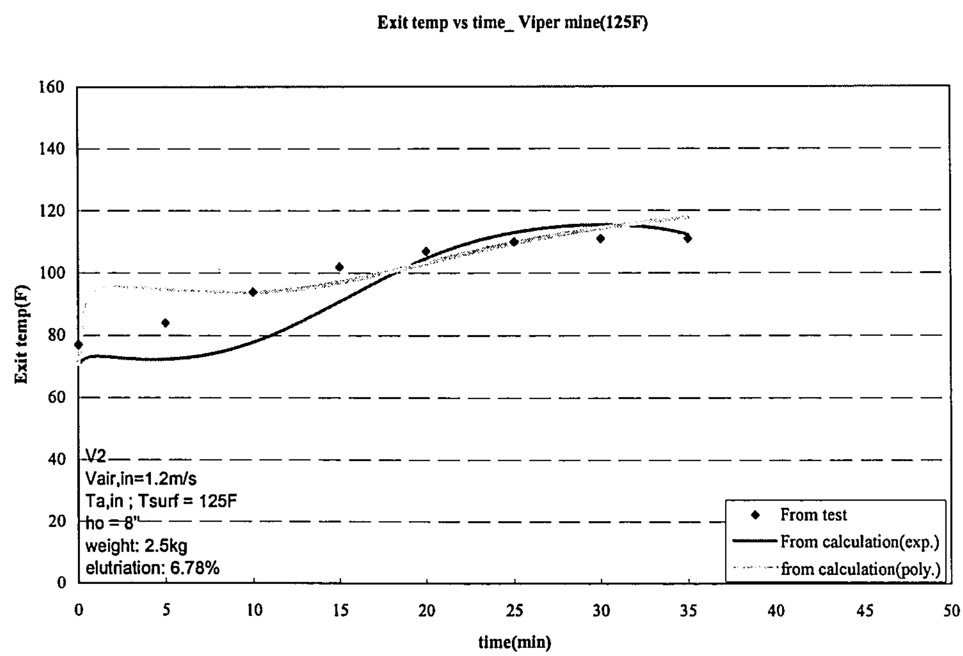

Fig 5.13 Exit air temperature simulation results _ Viper mine (125°F)

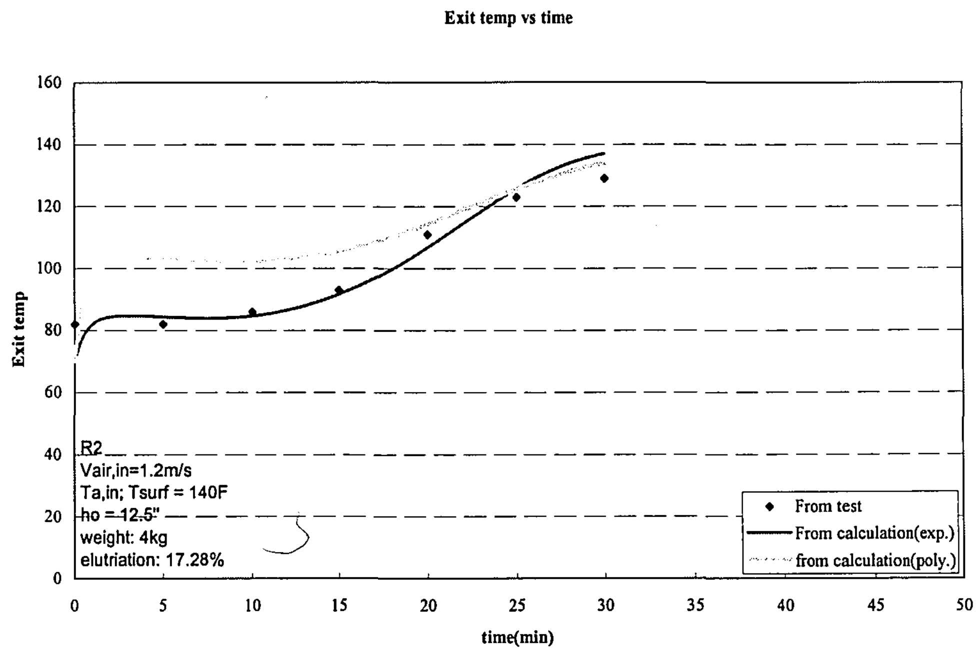

Fig 5.14 Exit air temperature simulation results _ Buckheart (140°F)

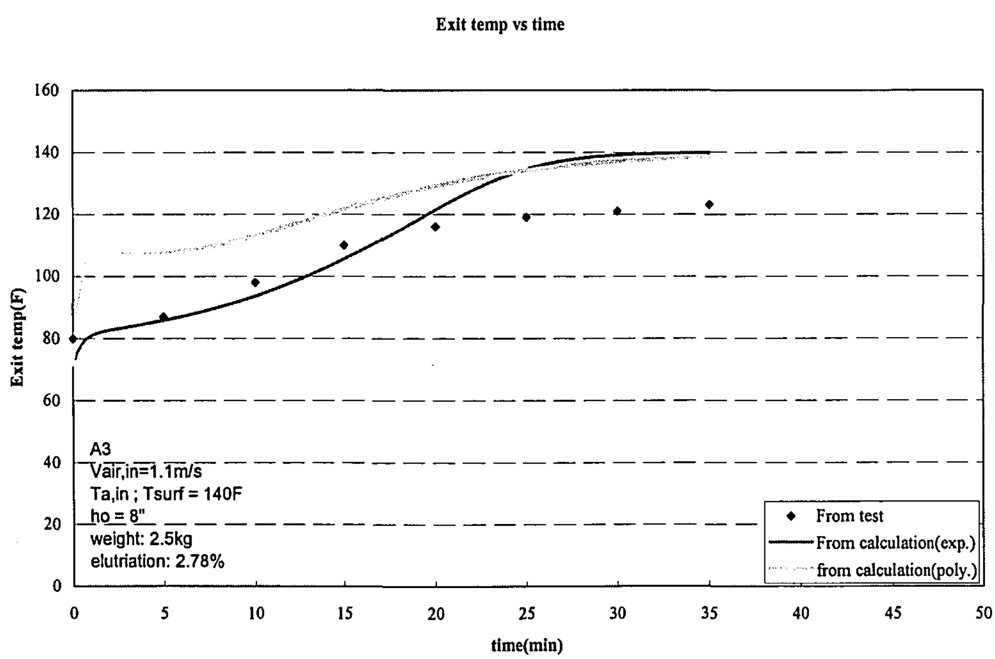

Fig 5.15 Exit air temperature simulation results _ Crown mine (140°F)

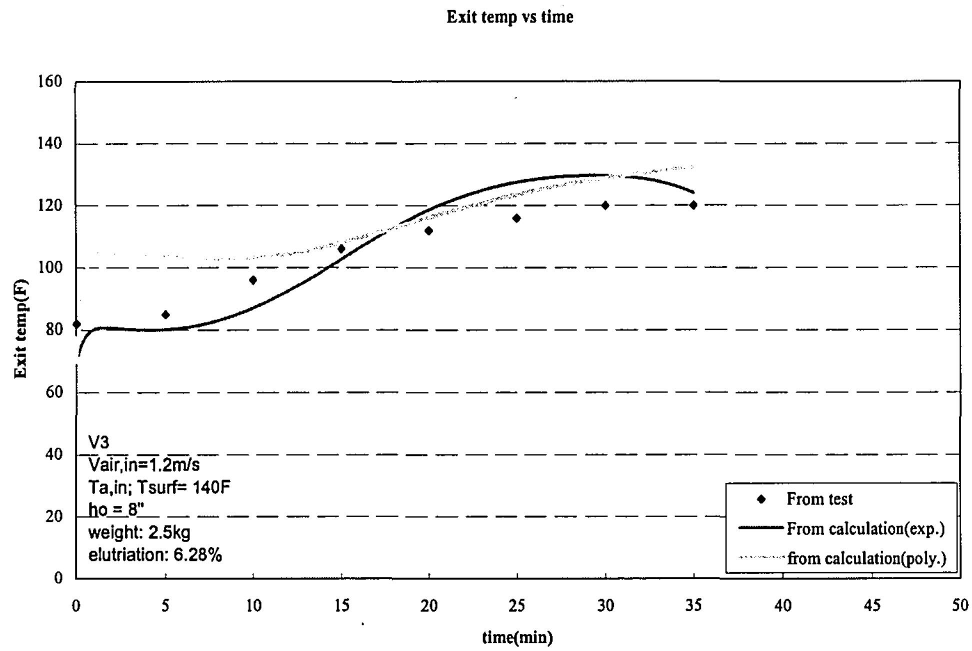

Fig 5.16 Exit air temperature simulation results _ Viper mine (140°F)

5.3 Exit specific humidity versus time

Fig 5.12~5.14 give the predictions for exit specific humidity. Obviously, Fig 5.12 shows a small error during the drying period. The predicted values were approximately 17.8% higher than the measured values at the beginning of drying test and 37.6% lower than the test values at the end. From equation (11), specific humidity comes from the calculation of relative humidity and saturation pressure, which are function of moisture content and exit air temperature. If more test data can be obtained to develop a more accurate equilibrium model, a prediction with excellent agreement to experimental results will be reached. Besides, the Crown mine and Viper mine models work very nicely for simulation.

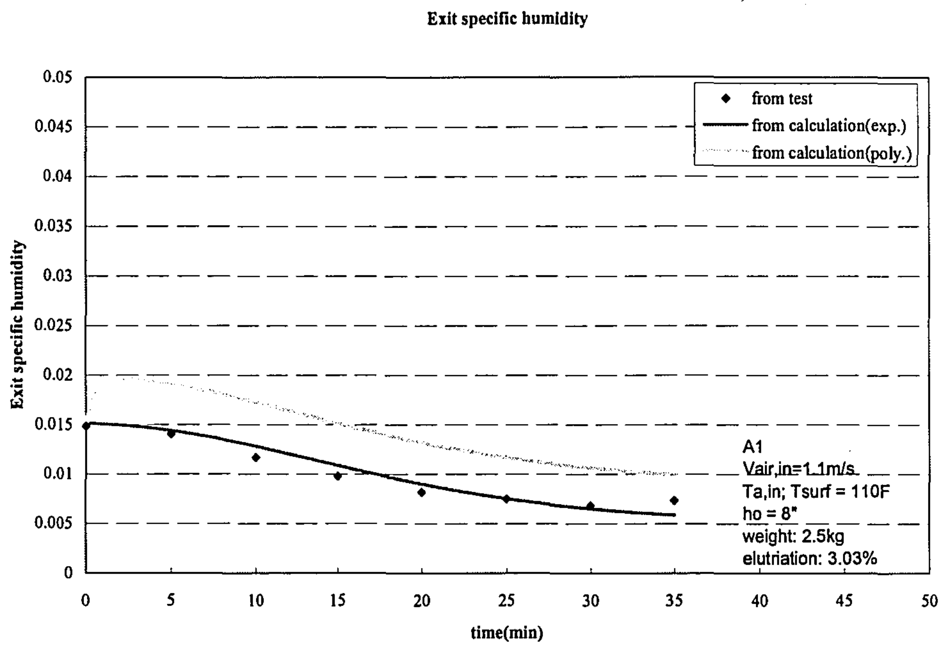

Fig 5.17 Exit specific humidity simulation results _ Crown mine (110°F)

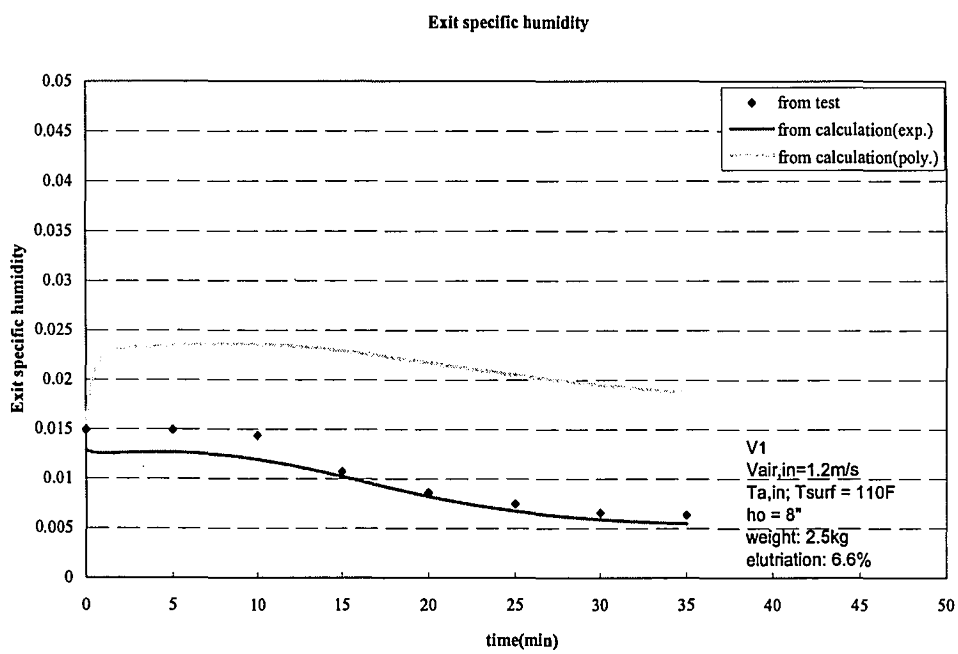

Fig 5.18 Exit specific humidity simulation results _ Viper mine (110°F)

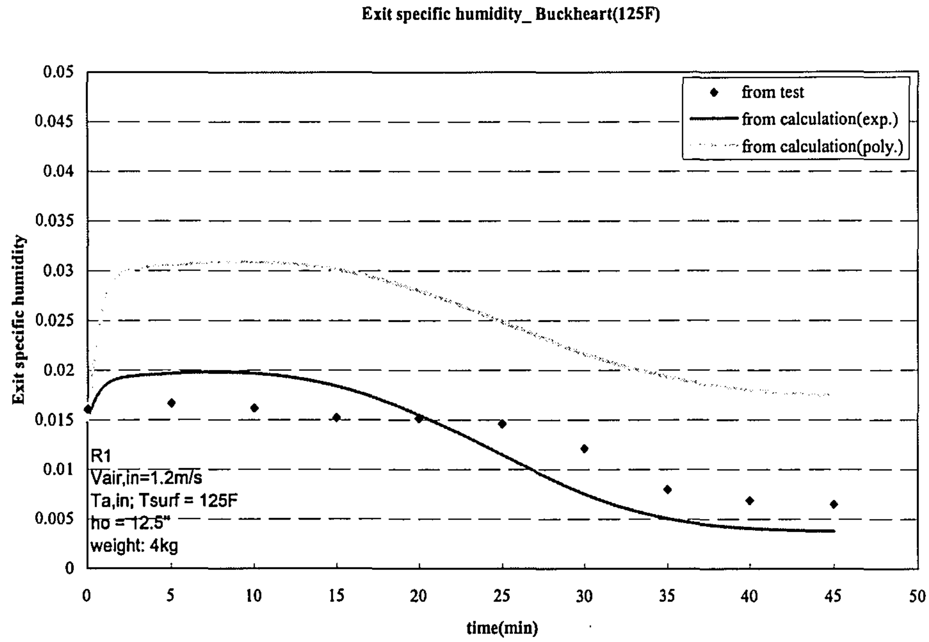

Fig 5.19 Exit specific humidity simulation results _ Buckheart (125°F)

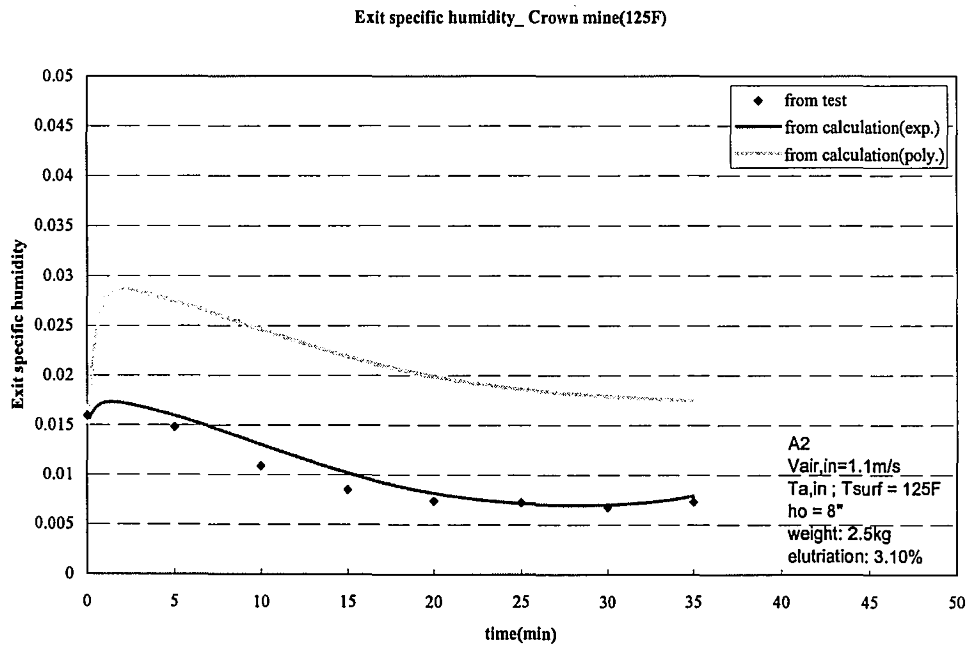

Fig 5.20 Exit specific humidity simulation results _ Crown mine (125°F)

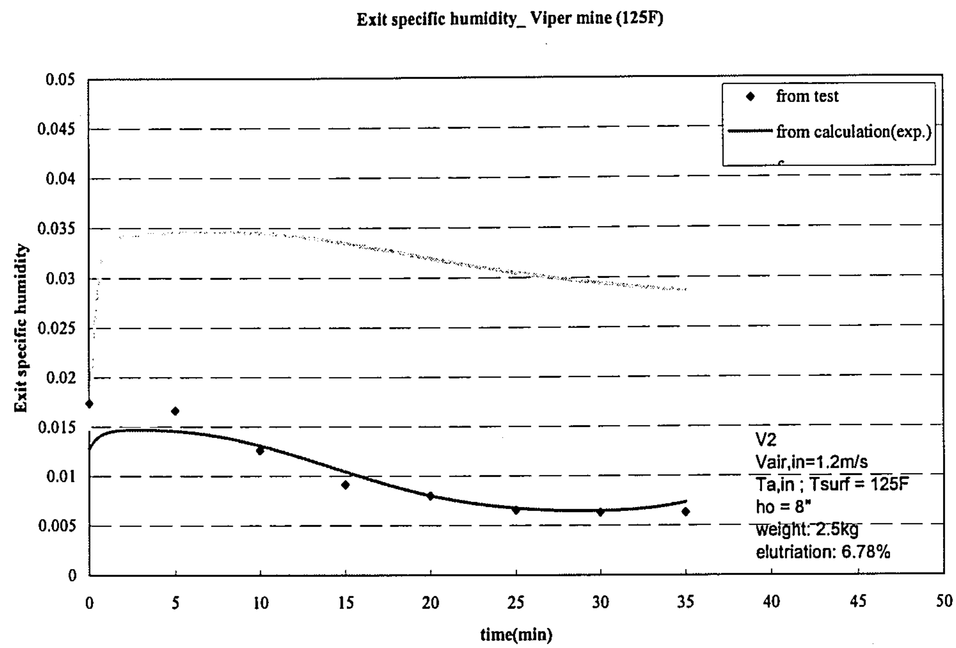

Fig 5.21 Exit specific humidity simulation results _ Viper mine (125°F)

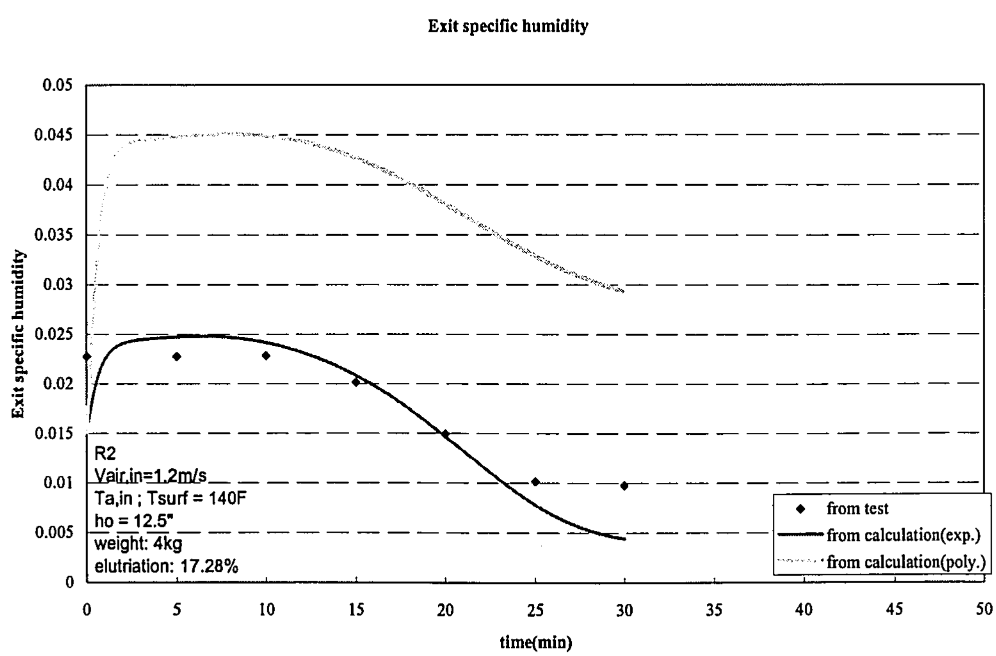

Fig 5.22 Exit specific humidity simulation results _ Buckheart (140°F)

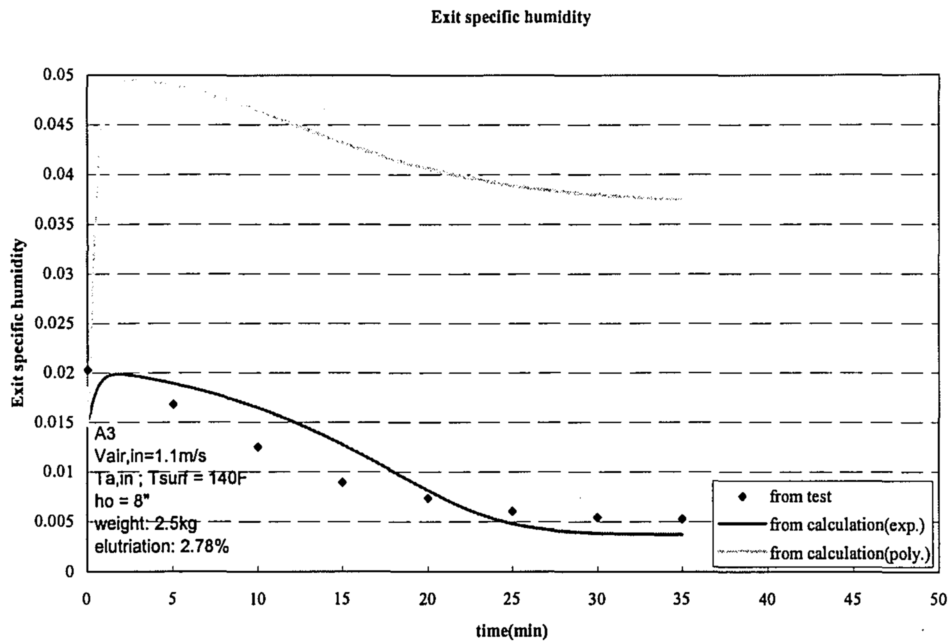

Fig 5.23 Exit specific humidity simulation results _ Crown mine (140°F)

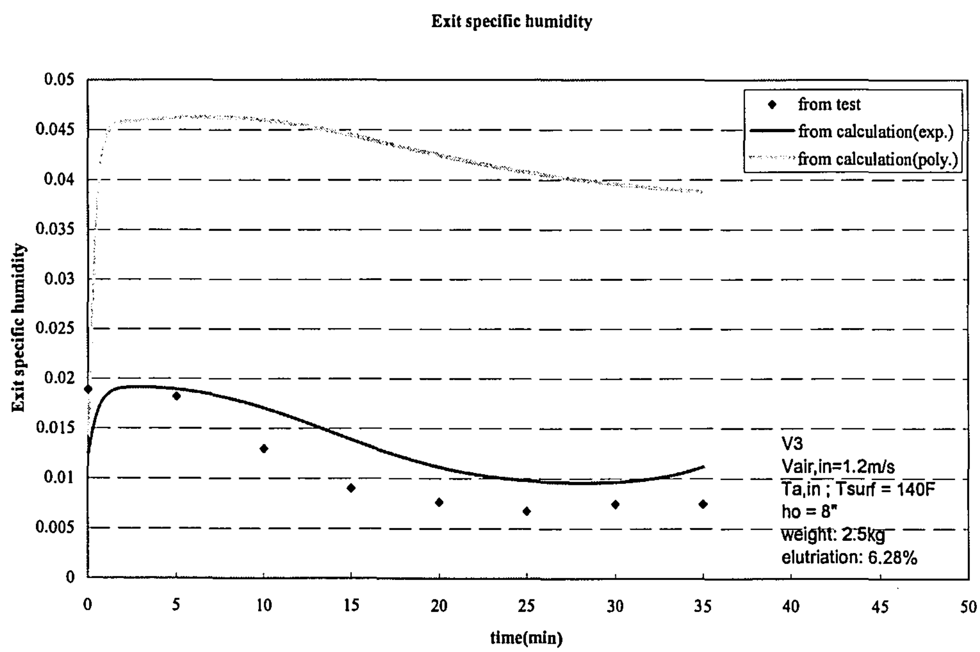

Fig 5.24 Exit specific humidity simulation results _ Viper mine (140°F)

5.4 Exit relative humidity versus time

Fig 5.15 ~ 5.17 present the comparison between theoretical and experimental results of exit relative humidity in 125°F drying temperature. The prediction results depend on the equations from numerical curve fitting in the graph of moisture content and relative humidity. In the previous research, Edward K. Levy et al. (Ref. 19) introduced a mathematical model which requires a relation for $\Gamma = \Gamma(\phi, T)$. However, this relation didn't work very well in the drying conditions of this study. From the following graphs, the model $\phi = f(\Gamma)$ is successful in describing the drying process.

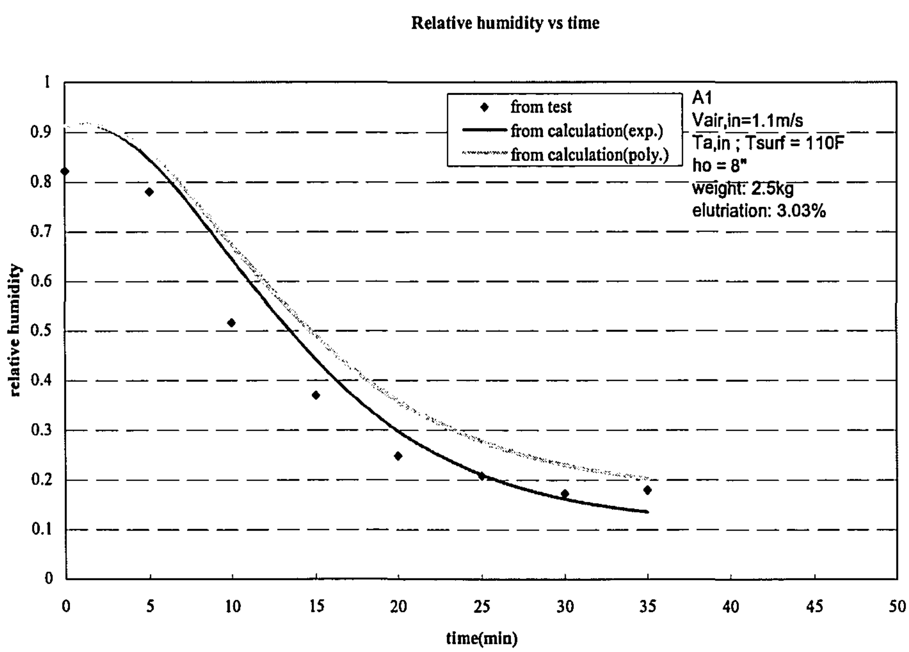

Fig 5.25 Exit relative humidity simulation results _ Crown mine (110°F)

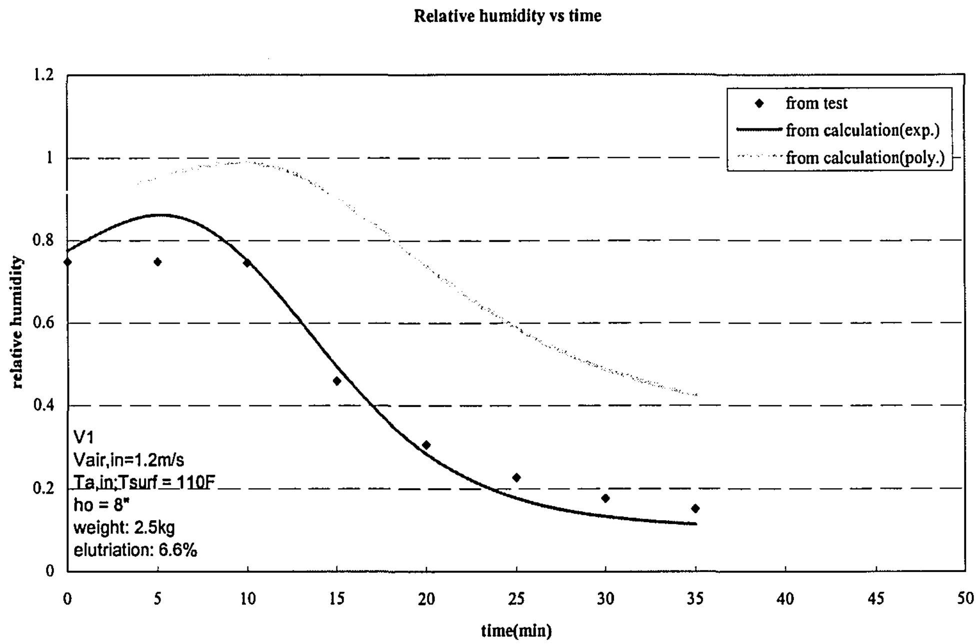

Fig 5.26 Exit relative humidity simulation results _ Viper mine (110°F)

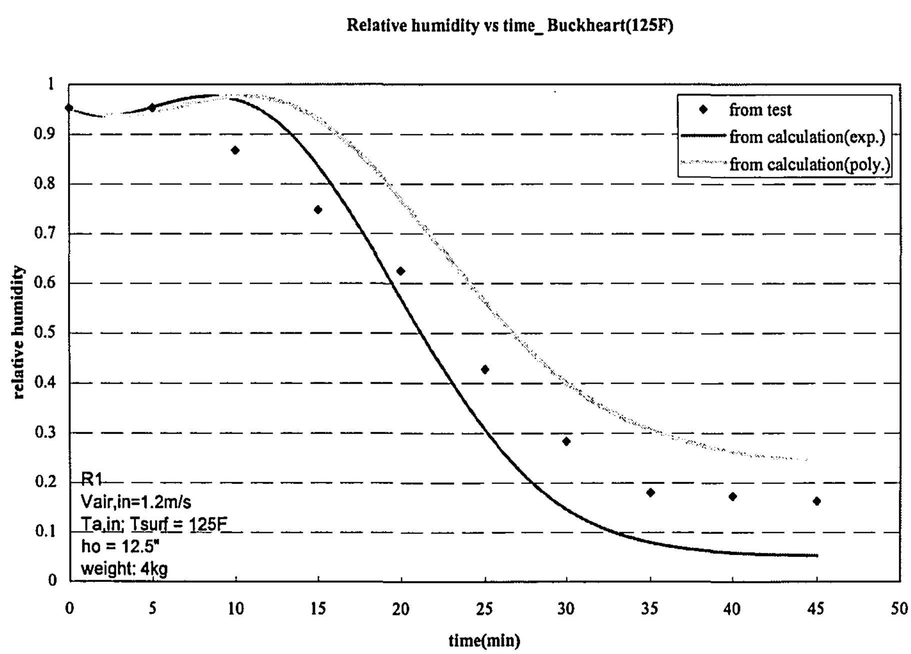

Fig 5.27 Exit relative humidity simulation results _ Buckheart(125°F)

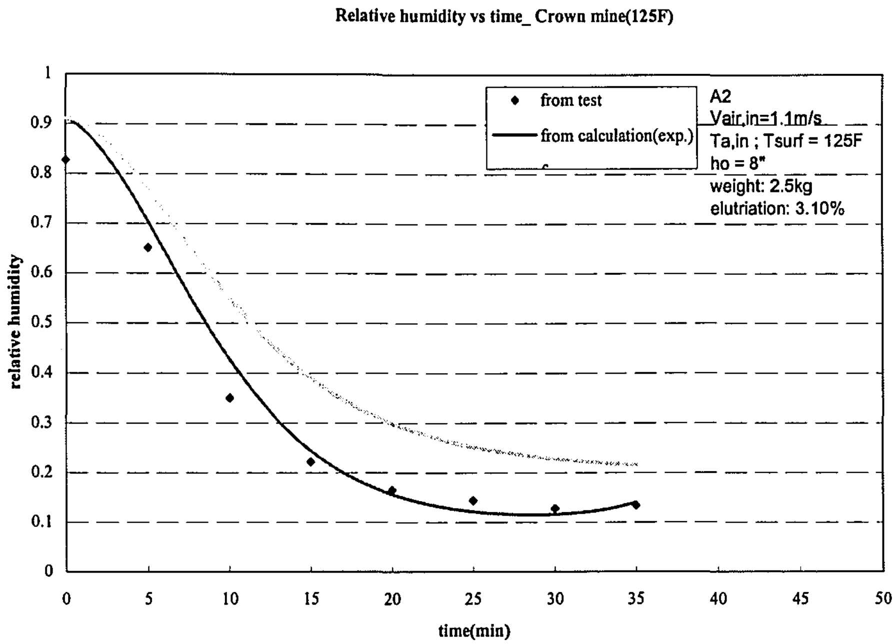

Fig 5.28 Exit relative humidity simulation results _ Crown mine (125°F)

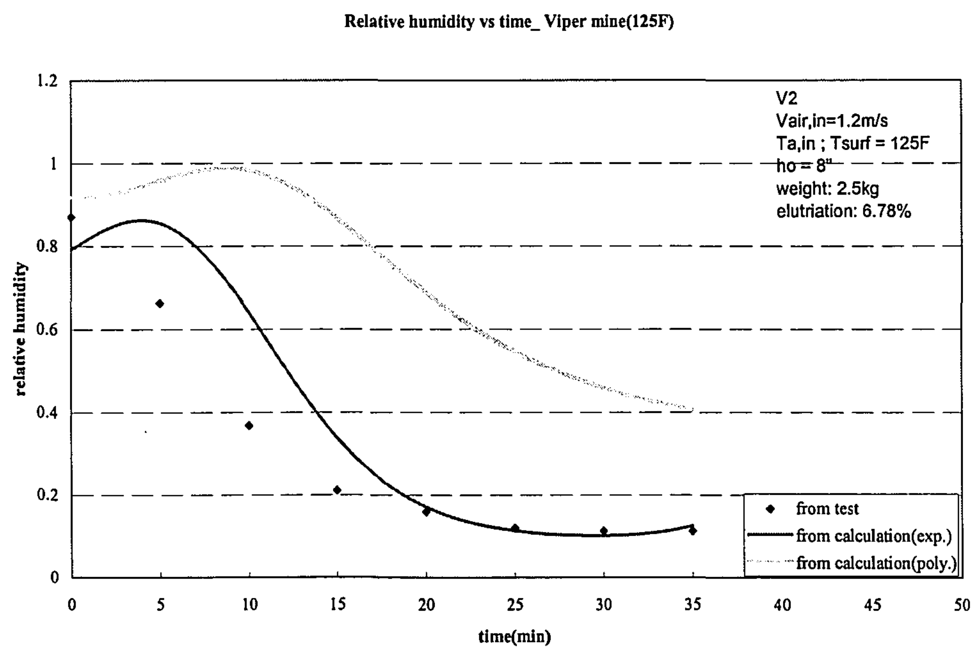

Fig 5.29 Exit relative humidity simulation results _ Viper mine (125°F)

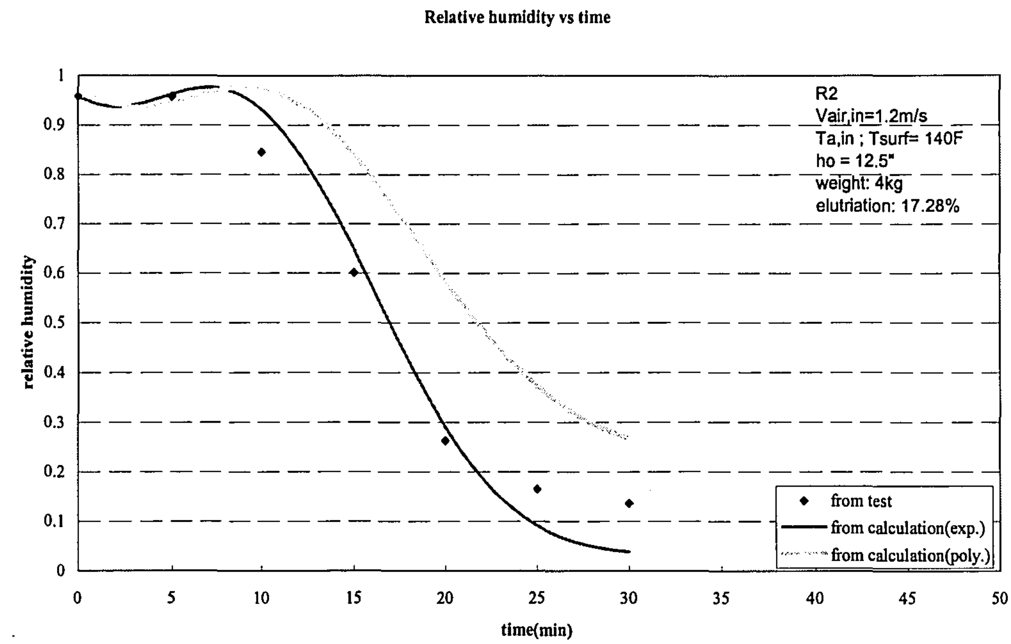

Fig 5.30 Exit relative humidity simulation results _ Buckheart (140°F)

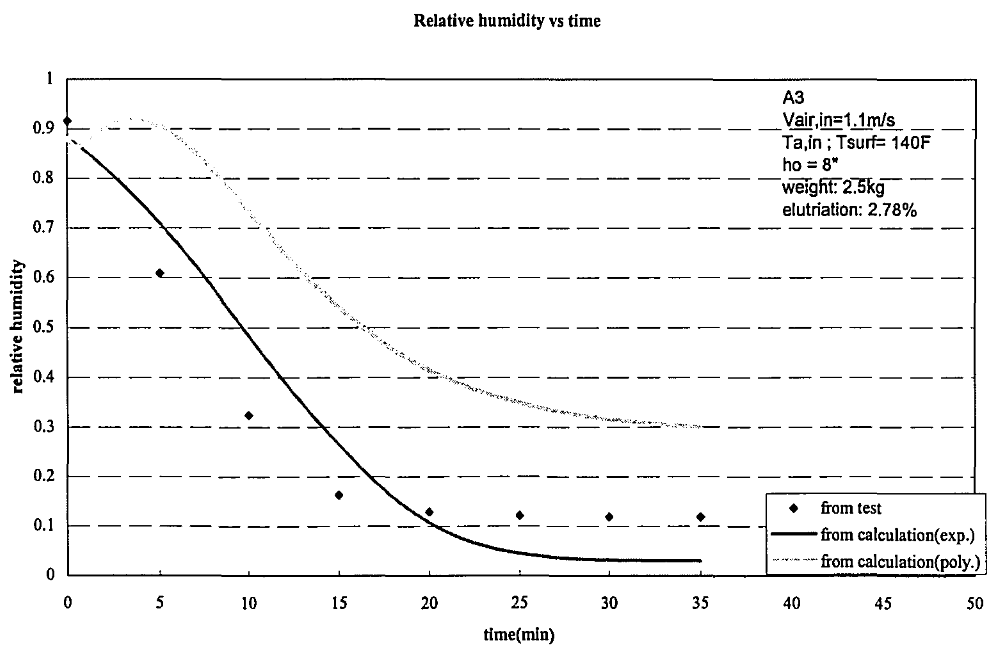

Fig 5.31 Exit relative humidity simulation results _ Crown mine (140°F)

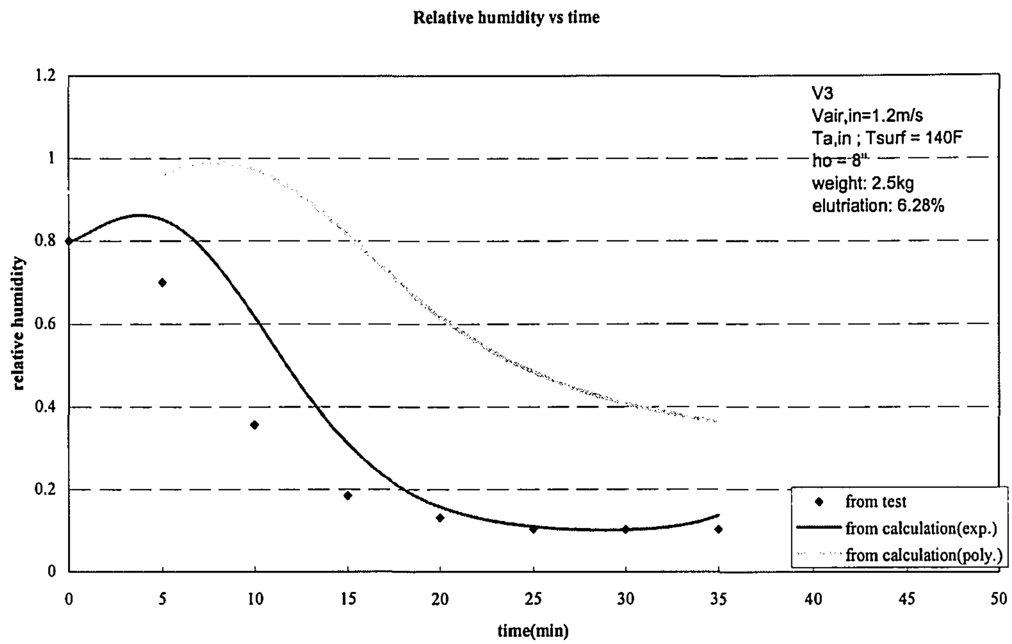

Fig 5.32 Exit relative humidity simulation results _ Viper mine (140°F)

5.5 Different type of coals

Comparisons for all of the test runs are given in Figure 5.33 ~ 5.37. Fig 5.33 compares predicted and measured values of moisture reduction, which is the difference between the initial and the end moisture content. Fig 5.34 and 5.35 show the test and simulation results of average exit air temperature and specific humidity. The measured values were the average values obtained from air temperature and humidity measurement downstream of the bed. The average values from the computer simulations were obtained by integrating exit air temperature and specific humidity from the initial to the end. For all types of coals, Fig 5.33 and 5.34 show an excellent agreement between the two results.

In Fig 5.35, the experimental data of the Viper mine coal with 140°F drying temperature (V3, V6) have 10~15% error comparing with predicted values. In Fig 5.36, the test results were the average relative humidity calculated from equation (4), and the predicted results were the average values obtained from the computed data using equation (13)~(15). From this graph, the Viper mine coal with higher drying temperature (V6) has a larger error than the other coals. Fig 5.37, which compares measured to predicted initial drying rates in the first 5 minutes, presents a bias error (Ref. 10) between the two. The experimental data were larger than calculated values by 12% to 25%. The error will be larger when the drying temperature was increased (R2, A3, A5, V3, V6).

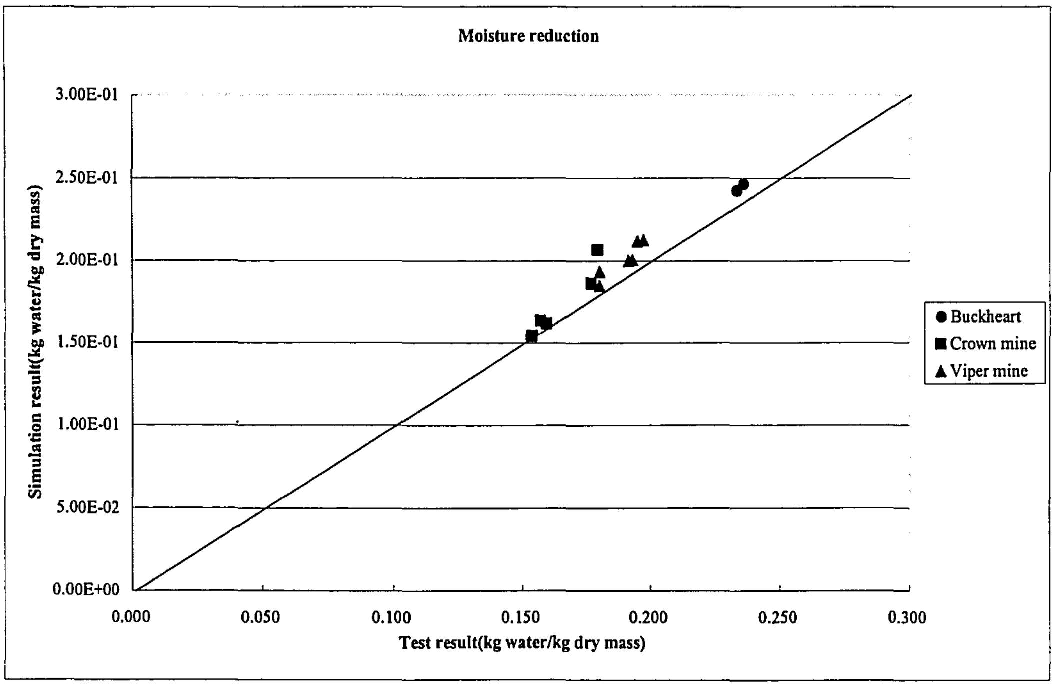

Fig 5.33 Comparison between simulation and test results _ change in moisture content

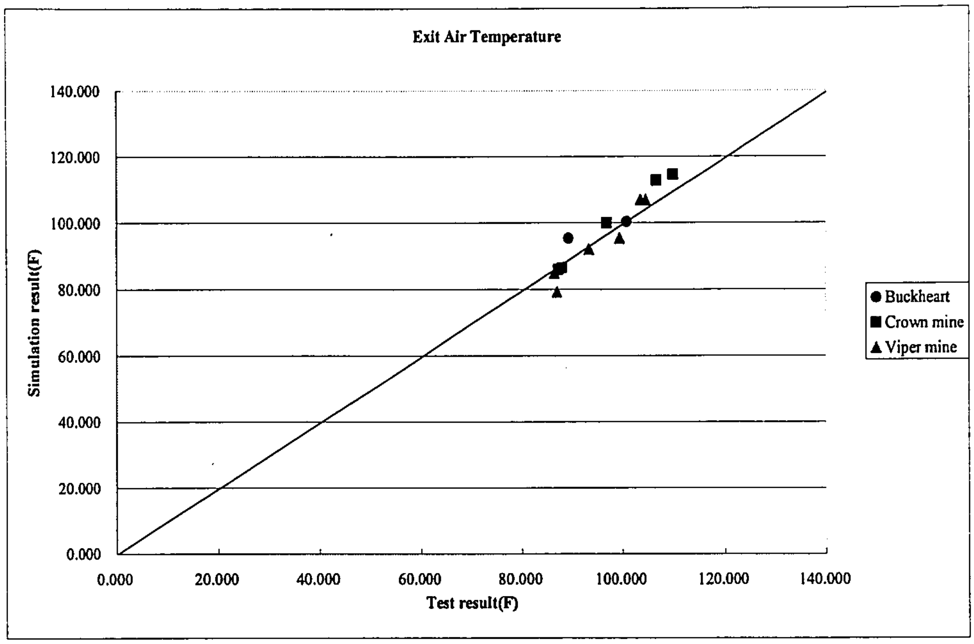

Fig 5.34 Comparison between simulation and test results _Average exit air temperature

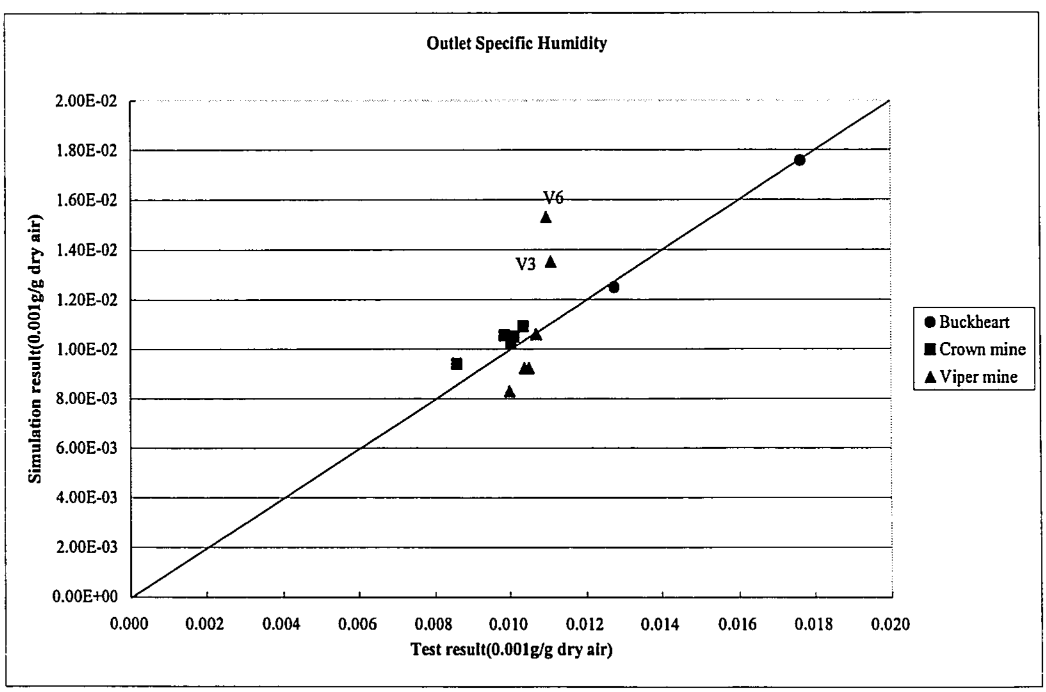

Fig 5.35 Comparison between simulation and test results _Average exit specific humidity

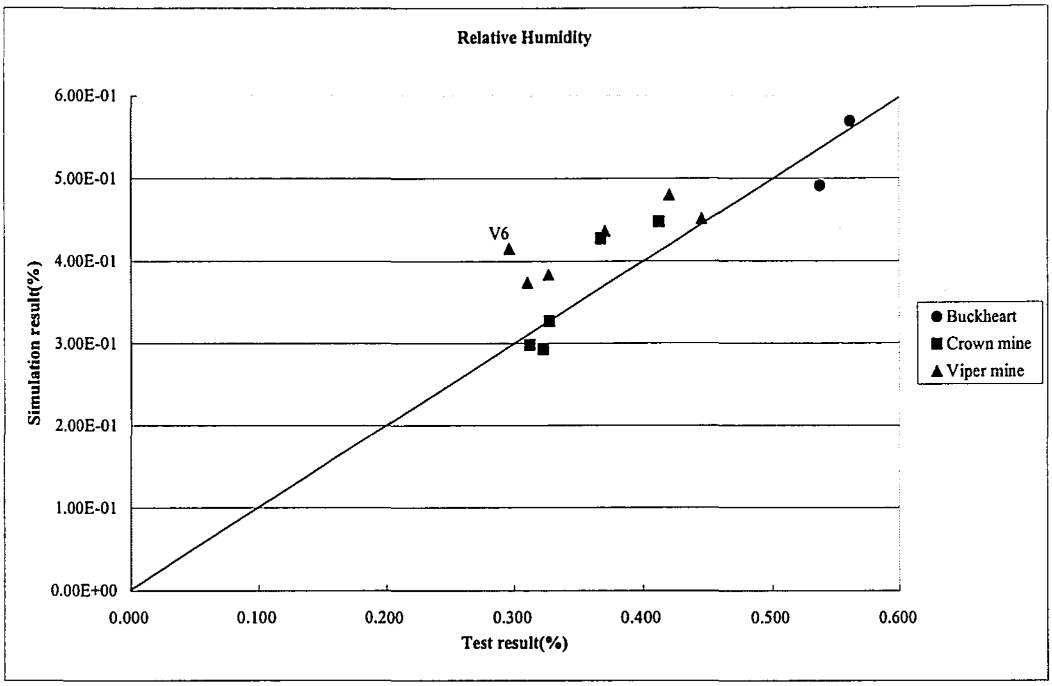

Fig 5.36 Comparison between simulation and test results _ Average exit relative humidity

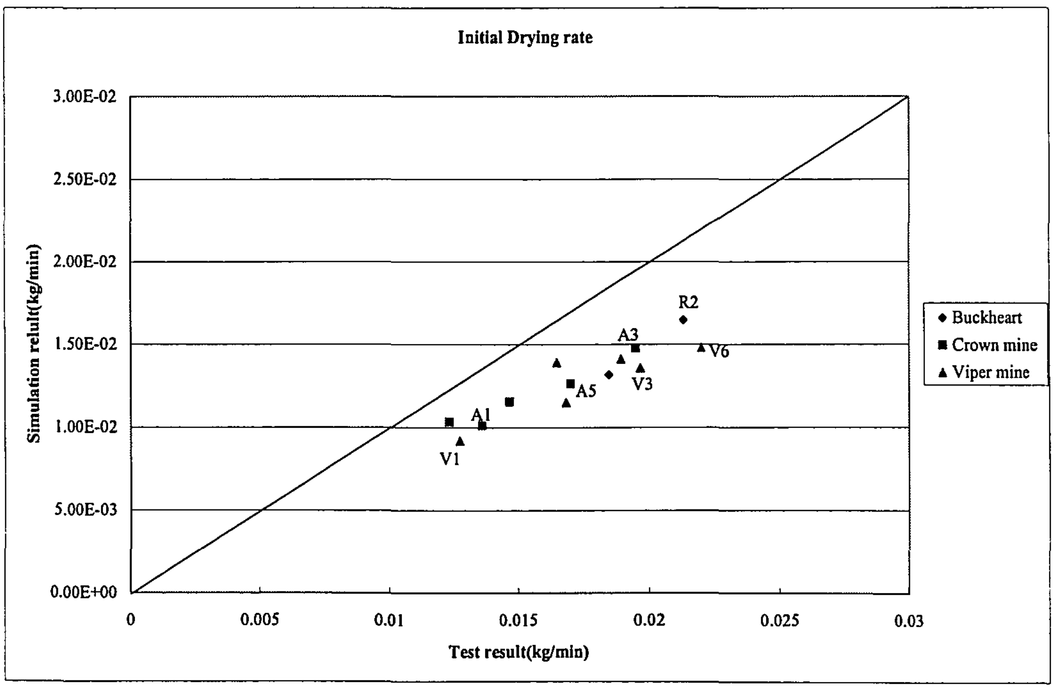

Fig 5.37 Comparison between simulation and test results _ drying rate

Chapter 6 Conclusions

The objective of this research was to use quantitative and qualitative methods for finding the factors which affect the drying performance of coals from the Buckheart, Crown and Viper mines. Experimental data were obtained to find the effects of drying temperature on drying rate for different kind of coals. A theoretical model based on all the drying conditions was also developed to predict the drying process and compare to test results. Systematic analysis of the experimental results leads to the following conclusions:

- The initial drying rate was increased by increasing the drying temperature. The drying rate of Viper mine has the most significant enhancement when drying temperature rises.
- With the smooth increasing of exit air temperature, as well as the consistency of top and bottom bed temperature, the coal in fluidized bed was considered to be well fluidized and mixed.
- The coal moisture content was considered to be reduced with the increase of difference between exit specific humidity and saturate air, and also between exit dry and wet bulb temperature.

- During the drying test, the wetter materials are, the lower heat transfer coefficient would be.
- For the Buckheart and Viper mine coals, the time required to reach the equilibrium moisture content was decreased when enhancing the drying temperature.
- Based on the initial drying rates, the drying performances of Viper mine was better than Crown mine. If they were based on the drying time to reduce the moisture content down to 20%, Crown mine was preferable.
- By analyzing numerically the relation between relative humidity (ϕ) and moisture content (Γ), the mathematical equations used to calculate the drying performance were established. The theoretical model of the drying process in this study is in excellent agreement with the laboratory data.
- The drying performance was more predictable in lower drying temperature than in higher drying temperature. When doing theoretical calculation, using the exponential functions to fit the test data was more proper than using the polynomial ones.

References

1. Edward Levy, "Use of Coal Drying To Reduce Water Consumed in Pulverized Coal Power Plants", DOE project DE-FC26-03NT41729, Quarterly Report for Jan 1st to March 31 , 2003
2. Bullinger , C., M. Ness, N. Sarunac, E.K. Levy, " Coal Drying Improves Performance and Reduces Emissions, " Presented at the 27th International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, Florida, March4-7, 2002
3. Wade A. Amos (1998), " Report on Biomass Drying Technology", National Renewable Energy Laboratory, GT818510
4. Edward Levy, Hugo Caram, Gu Feng, Zheng Yao, Zhang Wei, and Nenad Sarunac, " Fluidized Bed Coal Drying at Low Temperatures. "
5. Edward K. Levy, Hugo S. Caram, Zheng Yao, Zhang Wei and Nenad Sarunac, "Kinetics of Coal Drying in Bubbling Fluidized Beds." Fifth World Congress on Particle Technology, Orlando, Florida, April 2006
6. P.P. Thomas and Y.B.G. Varma , " Fluidized bed drying of granular food materials" , Powder Technology, Vol 69, pp 213-222, 1992
7. Julia ZH Gao, David B. Gray, Rajeshwar Motheram, Munir A. Hussain, " Importance of Inlet Air Velocity in Fluid Bed Drying of a Granulation Prepared in a High Shear Granulator", AAPS PharmSciTech, 2000, 1(4)
8. W.K.Ng, R.B.H. Tan, " Case study: Optimization of an industrial fluidized bed drying process for large Geldart Type D nylon particles", Powder Technology, in press, 2007
9. Z. Chen, W. Wu, P.K. Agarwal, "Steam –drying of coal. Part1. Modeling the behavior of a single particle", Fuel, Vol 79, pp961-973, 2000
10. Edward Levy, Nenad Srunac, Gu Feng, Wei Zheng, "Use of Coal Drying To Reduce Water Consumed in Pulverized Coal Power Plants", DOE project DE-FC26-03NT41729, Quarterly Report for Jan 1st to March 31, 2004
11. Daizo Kunii, Octave Levenspiel (1977)," Fluidization Engineering", New York
12. Edward K. Levy, " Effect of Temperature, Velocity and In-Bed Heat Flux on Lignite Drying Rate ", DOE project DE-FC26-03NT41729, May, 2003
13. C.M. van't Land (1991), " Industrial Drying Equipment", New York, pp 217-232
14. N.C. Diamond, T.R.A. Magee and G. McKay, " The effect of temperature and particle size on the fluid bed drying of Northern Ireland lignite", Fuel, Vol 69, issue 2, pp 189-193, Feb, 1990
15. Joao F. A. Vitor, Evaristo C. Biscaia Jr. and Giulio Massarani, " Modeling of Biomass Drying in Fluidized Bed", The 14th International Drying Symposium, Vol B,

pp.1104-1111, 2004

16. ASHRAE. 1993. " Psychrometrics", ASHRAE Fundamentals, pp6.1-6.21
17. H. Groenewold, E. Tsotsas, " Drying in fluidized beds with immersed heating elements", Chemical Engineering Science, Vol 62, pp493-498, September, 2006
18. Feng Gu, " Coal Drying In A Bubbling Fluidized Bed", Department of Mechanical Engineering and Mechanics, Lehigh University, May, 2004
19. Edward Levy, Nenad Srunac, Wei Zheng, "Use of Coal Drying To Reduce Water Consumed in Pulverized Coal Power Plants", DOE project DE-FC26-03NT41729, Quarterly Report for April 1st to June 30, 2004

VITA

Wei-Cheng Wang was born on May 9, 1979 in Taiwan. In 1997, he attended Feng-Chia University in Taichung, Taiwan to study Aerospace Engineering where he got his Bachelor of Science degree in June, 2001. In the following September, he entered Department of Mechanical Engineering, National Chung Cheng University to pursuit his higher education, where he received his Master of Science degree after two years. In January 2006, he began to study at Department of Mechanical Engineering and Mechanics in Lehigh University. He is now doing his Master of Science degree and working at the Energy Research Center under the guidance of Dr. Edward K. Levy.

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