Characteristics of Moisture Transfer and Surface Crack Development of a Single Lignite Particle Driven by Humidity Difference

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ABSTRACT: The research on moisture transfer characteristics and surface crack development of a single lignite particle (SLP) driven by humidity difference is helpful to achieve a better understanding of the fragmentation characteristics of lignite during the moisture transfer process. This is of great significance to the safe operation of a drying system. The characteristics of moisture transfer within SLP driven by humidity difference were studied in different stages. Six drying equations commonly used in the literature were selected to describe the moisture transfer behavior. The apparent diffusion coefficient ($D_{app}$) of moisture in each stage was calculated to compare the driving forces of moisture transfer in different stages. The surface crack rate (CR) was used to quantitatively analyze the fragmentation characteristics of SLP caused by moisture transfer. The results showed that the moisture transfer process of SLP driven by humidity difference can be divided into three stages, and stage I is the main moisture removal stage. The larger the particle size, the longer the stage I, while less moisture is removed in this stage. A logarithmic drying equation best simulates the moisture transfer process of SLP. The larger the particle size, the larger the $D_{app}$ value in each stage. The driving force of moisture transfer in stage I is the largest, which is the opposite of a thermal drying process. CR for SLP has experienced a rapid increase—stable at the highest value—rapid decrease—stable during the moisture transfer process driven by the humidity difference.

1. INTRODUCTION
Lignite plays an increasingly important role in China’s energy supply due to its large reserves, high reactivity, and low mining cost.1–4 It is also an important resource in the modern chemical industry. However, the high moisture content5,6 of lignite reduces its combustion efficiency,7 increases CO$_2$ emission, and transportation cost, which restricts the large-scale utilization of lignite. Therefore, it is necessary to reduce the moisture content of lignite before using it.

To dry lignite with high efficiency and low energy consumption, it is necessary to study the drying mechanism in more detail. Based on the theory of dry and wet zone, Li et al.8 established heat and mass transfer equations describing the drying process of a single lignite particle (SLP), and successfully predicted the drying behavior of lignite in high-temperature flue gas, including the temperature profile inside the particles and the migration of the dry–wet boundary. Wan et al.9 established a mathematical model to describe the drying process of lignite using the volume average method. Based on the model, the evolution and distribution of moisture, temperature, and water vapor pressure in lignite particles were studied. It was found that there was a moisture gradient in the lignite particles during drying, which was mainly affected by the water vapor pressure inside the particles and had little relationship with the acceleration of the drying rate caused by the increase of the drying temperature. In the classical drying theory, there is a humidity difference between the wet material and drying medium, and the pressure of water vapor on the surface or inside the wet material is greater than the partial pressure of water vapor in the drying medium. High temperatures increase the pressure difference, thus speeding up the drying process.

In the aspect of thermal fragmentation, the fragmentation mechanism is closely related to the thermal environment temperature and material properties, such as strength and permeability. For high strength and low permeability materials, such as concrete and castable, Barakat et al.10 used high-temperature nuclear magnetic resonance (NMR) to monitor the internal moisture profile of these materials during high-temperature drying. Combined with the measured temperature profile, the water vapor pressure inside the materials was calculated, and it was considered that water vapor pressure was...
the main cause of fragmentation. However, for the materials with low strength and high permeability, such as soils, scholars focus on the crack development caused by volume shrinkage during the drying process, and the drying process is mainly a moisture transfer process driven by the humidity difference. The strength and permeability of lignite are between those of cement and soil (shown schematically in Figure 1), so the contribution of internal gas pressure and drying shrinkage must be considered in the study of the lignite fragmentation mechanism. With respect to the high-temperature heat treatment of coal, Senneca et al. established a mathematical model to describe the fragmentation of coal particles under an inert atmosphere at high temperatures. The contribution to the fragmentation of coal particles at 800–2000 K is mainly due to the combined action of thermal stress and internal over-pressure caused by volatile matter release. However, for the low-temperature thermal drying process of lignite, Komatsu et al. observed surface cracks and shrinkage of lignite particles during drying at 110–170 °C, and found that surface cracks and significant shrinkage of lignite particles occurred during drying, and even the maximum shrinkage rate of lignite particles with a diameter of 10 mm could reach 41%. Due to the low temperature and moderate strength of lignite, the contribution of internal gas pressure to fragmentation is decreased, while the fragmentation effect caused by shrinkage is enhanced. Thus, fragmentation of lignite caused by shrinkage cannot be ignored during low-temperature drying.

To understand the low-temperature drying process and fragmentation characteristics of lignite better, the moisture transfer process inside lignite particles was driven by the humidity difference between inside and outside the lignite particles, and the influence of moisture transfer driven by moisture difference on the fragmentation process was studied. First, the moisture transfer process of SLP will be described in detail, including the drying curve and drying rate curve. Then the drying kinetics will be studied from two aspects of the drying equation and the apparent diffusion coefficient of moisture. Finally, the surface crack rate (CR) will be used to quantitatively describe the development of surface cracks during the whole moisture transfer process.

2. RESULTS AND DISCUSSION

2.1. Moisture Transfer Process. The results of proximate analysis and ultimate analysis of Zhaotong lignite are summarized in Table 1. As can be seen from Table 1, the moisture content of Zhaotong lignite is as high as 63.15%, and it has a high volatile matter yield and low fixed carbon.

| Material  | Material property | Temperature | Fragmentation mechanism |
|-----------|------------------|-------------|-------------------------|
| soil      | low strength     | high        | shrinkage               |
| lignite   | high strength    | low         |                         |
| cement    | high strength    | high        |                         |

Figure 1. Schematic representation focusing on the main characteristics of soil, lignite, and cement in relation to crack formation in drying.

Table 1. Proximate Analysis and Ultimate Analysis of Zhaotong Lignite

| moisture (wt basis, %) | proximate analysis (wt %, db) | ultimate analysis (wt %, daf) |
|------------------------|-------------------------------|-----------------------------|
| 63.15                  | volatile matter              | C                           |
| 47.38 ± 0.56           | fixed carbon                 | H                           |
| 34.89 ± 0.53           | ash yield                    | N                           |
| 17.73 ± 0.20           |                                 | S                           |
| 32.65 ± 0.79           |                                 | O                           |

The six equations listed in Table 3 (see Section 4.3) were used to describe the moisture transfer behavior of SLP with different sizes under the driving force of a humidity difference. Each equation was fitted with two sets of

In Figure 2A the measured moisture content as a function of time driven by humidity difference for SLP with different side lengths are given in a 20 °C and 70% relative humidity (RH) environment. As can be seen at the beginning of the experiment, the moisture content decreases rapidly, and after a short transition zone, the moisture content of samples tends to stabilize. The smaller the particle size is, the faster the moisture content decreases at the beginning of the experiment. At the end of the experiment (i.e., after more than 70 h), the moisture content of the sample tends to stabilize and the residual moisture content of the sample increases with the increase of the side length of the cube at this stage.

The MTRs were calculated based on eq 2 (see Section 4.2.), and are shown in Figure 2B. Only the lignite sample with a particle size of 30 mm observed the increase of MTR at the beginning of drying, that is, MTR increases to the maximum value in a short time with the decrease of the moisture content at the beginning of drying. After this, MTR decreases with a decrease in the moisture content. For the other two small particles, MTR reaches the maximum value at the beginning of the experiment, then goes through a short constant rate stage, and finally decreases with the decrease of the moisture content. For the entire process of moisture removal, the bigger the side length of SLP, the smaller the MTR. In addition, the MTR of SLP in the process of moisture transfer driven by humidity difference experiences the same process as that in the hot air drying process, but the value is much smaller than that of the hot air drying process.
data, i.e., each experiment was performed twice. The equation coefficients and the evaluation of the fit for the six equations used are listed in Table 2. The range of $R^2$, standard error of the estimate (SSE), and root mean square of errors (RMSE) in Table 3 are 0.9475–0.9973, 0.0076–0.1485, and 0.0121–0.0602, respectively. As can be seen from Table 2, compared

![Figure 2](image1.png)

**Figure 2.** Measured moisture content as a function of time (A) and the moisture transfer rate (MTR) curves (B) of the various moisture transfer samples driven by a humidity difference (the relative error of $X$ is less than 8%).

![Figure 3](image2.png)

**Figure 3.** Mass as a function of time for various cubes. Different moisture transfer stages of SLP with side lengths of (A) 30 mm, (B) 20 mm, and (C) 10 mm are indicated by stages I, II, and III. Moisture removal quantity at different stages is given in (D) (the relative error of $X$ is less than 8%).
behavior within SLP driven by humidity di
compared to the model prediction based on the equations. As
Figure 4, the MR as determined from the experiments is
which also proves the accuracy of the calculation process. In
logarithmic equation between the two duplicates are very close,
all particle sizes is almost the largest and close to 1, and SSE
with other equations,

Table 2. Parameters and the Evaluation of the Fit for Six Equations

| sample        | equation name     | parameter | R²   | SSE  | RMSE  |
|---------------|-------------------|-----------|------|------|-------|
| 30 x 30 x 30 mm | Henderson and Pabis | \( a_1 = 1.017, k_1 = 2.767 \times 10^{-3} \) | 0.9934 | 0.0213 | 0.0217 |
| page          | Henderson and Pabis | \( a_2 = 1.042, k_2 = 2.631 \times 10^{-3} \) | 0.9943 | 0.0199 | 0.0210 |
| logarithmic   | Henderson and Pabis | \( k_1 = -1.785 \times 10^{-5}, n_1 = 1.023 \) | 0.9933 | 0.0217 | 0.0220 |
| two term      | Henderson and Pabis | \( k_2 = -1.662 \times 10^{-5}, n_2 = 1.039 \) | 0.9931 | 0.0239 | 0.0251 |
| diffusion     | Henderson and Pabis | \( a_1 = 1.009, c_1 = 0.027, k_1 = 3.036 \times 10^{-3} \) | 0.9964 | 0.0118 | 0.0164 |
| approximation | Henderson and Pabis | \( a_2 = 1.034, c_2 = 0.022, k_2 = 2.825 \times 10^{-3} \) | 0.9960 | 0.0140 | 0.0178 |
| Henderson and Pabis | \( a_3 = 0.535, k_3 = 3.706 \times 10^{-3} \) | 0.9966 | 0.0174 | 0.0197 |
| Henderson and Pabis | \( a_4 = 0.667, k_4 = 2.903 \times 10^{-3} \) | 0.9992 | 0.0247 | 0.0234 |
| Henderson and Pabis | \( a_5 = 1.043, b_1 = 0.5091, k_5 = 3.356 \times 10^{-3} \) | 0.9956 | 0.0142 | 0.0180 |
| Henderson and Pabis | \( a_6 = 1.048, b_2 = 0.789, k_6 = 2.878 \times 10^{-3} \) | 0.9935 | 0.0227 | 0.0227 |

Table 3. Equations Established to Describe the Change of the Moisture Content with Time During Drying

| equation name     | equation |
|-------------------|----------|
| Henderson and Pabis | \( MR = a \exp(-kt) \) |
| logarithmic       | \( MR = \exp(kt^2) \) |
| two-term exponential | \( MR = a \exp(-kt) + (1 - a)\exp(-kt) \) |
| diffusion approximation | \( MR = a \exp(-kt) + (1 - a)\exp(-kt) \) |
| modified Henderson and Pabis | \( MR = a \exp(-kt) + b \exp(-gt) + c \exp(-lt) \) |

with other equations, \( R^2 \) of the logarithmic drying equation for all particle sizes is almost the largest and close to 1, and SSE and RMSE are also the smallest. The parameters of the logarithmic equation between the two duplicates are very close, which also proves the accuracy of the calculation process. In Figure 4, the MR as determined from the experiments is compared to the model prediction based on the equations. As can be seen, a clear linear relation is found, indicating that this equation can be used to describe the moisture transfer behavior within SLP driven by humidity difference.

Figure 4. Predicted MR by the logarithmic drying equation vs experimentally determined MR.

2.3. Apparent Diffusion Coefficient. To determine the \( D_{eff} \) of SLP in different moisture transfer stages under the driving force of humidity difference, ln MR vs t is plotted in
Figure 5. The moisture transfer process is divided into three stages, as shown in Figure 3. In Figure 5, these three stages are fitted, respectively. The fitting results are also listed in Figure 5. Based on these fitting results the $D_{eff}$ values of moisture in SLP for the various stages are given in Figure 6.

Figure 6 shows $D_{eff}$ of moisture in three samples with different side lengths under the driving force of humidity difference. The higher $D_{eff}$ value indicates that the moisture transport in the sample is higher and the moisture can be removed easily. As side length increases, $D_{eff}$ shows an increasing trend. For different stages of the moisture transfer process, it shows the same trend, that is, $D_{eff}$ is proportional to $L^2$. The larger the particle size of the lignite sample, the greater the difference in the water vapor concentration inside and outside the sample, the stronger the driving force of the mass transfer. After drying for the same time, there is still more moisture in the large particles compared with the small particles because the rate of moisture removal is smaller, so the humidity difference between the inside and outside of the large particles is larger, that is to say, the large particles of lignite always have greater moisture transport force. In addition, it is also clear from Figure 6 that $D_{eff}$ of stage I is much larger than the other two stages. In stage I, the sample has the highest moisture content, so the driving force for the moisture transfer in the particle is the largest. This is different from the thermal drying process of lignite particles. Because of the destruction of the pore structure of lignite in an extreme thermal environment, the resistance of moisture transfer in lignite decreases, so $D_{eff}$ of lignite in the later stage of thermal drying is larger than that in the early stage. However, under the driving force of humidity difference in this study, the gel structure of lignite is preserved because of the low-temperature
and high humidity environment, so \( D_{\text{eff}} \) does not show an increasing trend with drying time in this study.

Figure 7 summarizes the surface crack development of SLP with a side length of 20 mm in the process of moisture transfer under the driving force of humidity difference. It can be seen that there are almost no cracks on the surface of the sample at the start of the experiment (drying time is 0 h). After 8 h of drying at 20 °C and 70% RH, a large number of cracks appear on the surface of the sample, but these cracks are relatively narrow. After 14 h, the number of surface cracks increases slightly, but as can be seen, the cracks all become wider. After that, the surface cracks of the sample hardly change until the drying time is 25 h. After 36 h, the surface cracks decrease, which is reflected in Figure 7, i.e., the cracks shrink and become narrow. After 44 h, it can be seen that cracks shrink greatly and become fine cracks. Finally, cracks continue to shrink and even partially close. A similar crack shrinkage phenomenon is observed at the end of superheated steam drying of lignite. Generally speaking, in the whole drying process of SLP driven by the humidity difference, the surface cracks experience a process of rapid development, stability, and shrinkage. The crack development process is consistent with low-temperature thermal drying, but the number of fine cracks is much less than that in low-temperature thermal drying.

To quantitatively explore the change of crack development in the whole moisture transfer process, the CR is given as a function of time in Figure 8. The CR increases sharply from 0 in stage I. At the same time, a large amount of moisture is removed rapidly. After entering stage II, the moisture removal rate of the sample is slowed down, and the CR grows slowly and then begins to decline during this stage. The moisture content of the sample almost reaches an equilibrium in stage III. The CR falls and then remains at almost an constant level during this stage. In general, the CR of the lignite sample has experienced a rapid increase — stable at the highest value — rapid decrease — stable during the moisture transfer process. This is consistent with the overall trend of crack development during thermal drying.

3. CONCLUSIONS

(1) The moisture transfer process for SLP can be divided into three stages, of which stage I is the main moisture removal stage. The larger the particle size, the longer the stage I, while less moisture is removed in this stage.

(2) A logarithmic drying equation can accurately describe the moisture transfer behavior of SLP driven by the humidity difference.

(3) The larger the particle size of the lignite sample, the larger the \( D_{\text{eff}} \) value describing the drying for that particle size in each stage, and the stronger the driving force of moisture transfer. The moisture transfer driving force of SLP with different sizes is the largest in the first stage, which is different from the thermal drying process of lignite particles.

(4) Surface crack development of SLP caused by moisture transfer under the driving force of humidity difference is consistent with that of lignite during thermal drying, that is, a rapid increase — stable at the highest value — a rapid decrease — stable.

4. METHODS AND EQUIPMENT

4.1. Sample. In this study, we have made use of lignite from Zhaotong, Yunnan Province (southwest China). According to the standard GB/T212-2008, a 5E-MAG6700 proximate analyzer from Changsha Kaiyuan Instrument Co. Ltd., was used to determine the moisture, ash, volatile matter, and fixed carbon content. Additionally, an ultimate analysis was carried out using a vario MACRO cube from Elementar Co. Ltd. The outer layer of a lignite sample can readily dewater or oxidize during storage. Therefore, the outer layer of Zhaotong lignite was stripped and the fresh inner core was cut into regular cubes with side lengths of 30, 20, and 10 mm in this study. Samples of the same size were randomly selected in subsequent experiments.

4.2. Moisture Transfer Experiment. To measure the moisture transfer of SLP samples a climate chamber was used, i.e., a LRHS-101B0LJS constant temperature and humidity chamber (Shanghai Linpin Instrument Stock Co., Ltd.). This chamber was used to provide a constant humidity environment for SLP, so as to realize the moisture transfer within SLP driven by lower external humidity. A schematic illustration of a constant temperature and humidity chamber is shown in Figure 9. It is mainly composed of a temperature control system and a humidity control system. A dry bulb and a wet-
bulb thermometer were used to determine the humidity in the sample chamber. The experimental conditions of constant temperature and humidity chamber were: a temperature of 20 °C with a constant relative humidity (RH) of 70%. A watchglass with a diameter of 90 mm was used to hold lignite cubes. After recording the weight, the watchglass with SLP was put into the sample chamber. To determine the mass decrease as a function of time during the moisture transfer experiments, the watchglass with SLP was taken out from the sample chamber every hour, weighed, and put back into the sample chamber to continue the moisture transfer experiment. The experiment was continued until the weight change rate was less than 1%. Each test was conducted twice.

To determine the drying curve, i.e., the moisture content loss as a function of time and thereby the moisture transfer behavior of SLP driven by the humidity difference, we have to relate to the constant dry mass of the sample. The moisture content of the sample on a dry basis \((X, \text{g/g-lignite, dry})\) can be calculated by

\[
X = \frac{m_i - m_0(1 - M_0)}{m_0(1 - M_0)} \tag{1}
\]

where \(m_i\) is the initial mass of SLP (g); \(m_t\) is the mass of SLP at time \(i\) (g); and \(M_0\) is the total moisture content of the Zhaotong lignite sample, as listed in Table 1, i.e., 63.15%.

Based on measured moisture content \(X\) as a function time, moisture transfer rate [MTR, g/(g·s)] was calculated by

\[
\text{MTR} = -\frac{dX}{dt} \tag{2}
\]

where \(t\) stands for time in seconds.

### 4.3. Kinetics Modeling

In this study, the moisture ratio (MR)\(^21\) was used to describe the moisture transfer behavior of SLP driven by the humidity difference, which can be calculated by

\[
\text{MR} = \frac{M_t - M_i}{M_0 - M_e} \tag{3}
\]

where \(M_t\) is the moisture content at time \(t\) (%) and \(M_e\) is the equilibrium moisture content (%). However, \(M_e\) is difficult to determine in experiments. Hence, \(M_i\) was replaced by the final moisture content, i.e., \(M_t\) (%).\(^21\) Therefore, eq 3 can be rewritten as

\[
\text{MR} = \frac{M_t - M_i}{M_0 - M_t} \tag{4}
\]

In the literature,\(^22\) various relations are given to predict the change in the moisture content with time during drying. The most common equations used are summarized in Table 3.

To determine the best fit for the various equations used, the coefficient of determination \((R^2)\), standard error of the estimate (SSE), and root mean square of errors (RMSE) were evaluated. The \(R^2\), SSE, and RMSE can be calculated by eqs 5–7, respectively.\(^25,26\)

\[
R^2 = 1 - \frac{\sum_{i=1}^{N}(\text{MR}_{\text{exp},i} - \text{MR}_{\text{pre},i})^2}{\sum_{i=1}^{N}(\text{MR}_{\text{pre},i} - \text{MR})^2} \tag{5}
\]

\[
\text{SSE} = \sum_{i=1}^{N} (\text{MR}_{\text{exp},i} - \text{MR}_{\text{pre},i})^2 \tag{6}
\]

\[
\text{RMSE} = \left[ \frac{1}{N} \sum_{i=1}^{N} (\text{MR}_{\text{exp},i} - \text{MR}_{\text{pre},i})^2 \right]^{1/2} \tag{7}
\]

where \(\text{MR}_{\text{exp},i}\) is the experimental value, \(\text{MR}_{\text{pre},i}\) is the predicted value based on the equation used, \(\text{MR}\) is the average of experimental values, and \(N\) is the number of experiments. A higher value of \(R^2\) and lower values of SSE and RMSE means that the equation has a better fit to the experimental data.

### 4.4. Apparent Diffusion Coefficient

We will assume that the moisture transport within lignite can be described on basis of a diffusion equation. The experimentally determined diffusion coefficient can be used to evaluate the mass transfer rate in a moisture transfer process.\(^27\) To do so according to the literature,\(^27\) the following assumptions need to be made,

(i) The initial moisture is evenly distributed in the lignite coal particles;

(ii) Moisture diffuses from the inside of lignite particles in the form of water vapor;

(iii) Drying speed depends on the moving speed of drying front;

(iv) The diffusion coefficient is constant and the volume shrinkage is ignored;

(v) The cube used in this experiment can be approximated by a sphere.

Using these assumptions, Fick’s second law can be used to describe the moisture diffusion process within SLP, and the overall moisture content is given by

\[
\text{MR} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n + 1)^2} \exp \left[ -\frac{(2n + 1)^2 \pi^2 D_{\text{eff}} t}{R^2} \right] \tag{8}
\]

where \(D_{\text{eff}}\) is the apparent diffusion coefficient \((\text{m}^2\cdot\text{s}^{-1})\) and \(R\) is the thickness of the sample (m). Here, the cube used in this experiment can be approximated to a sphere, so \(R\) can be replaced by half the side length of the cube \((L/2)\). We can take the first term as a good first-order approximation to predict the change of the moisture content of SLP with time driven by humidity difference, thus eq 8 can be rewritten as

\[
\text{MR} = \frac{6}{\pi^2} \exp \left[ -\frac{\pi^2 D_{\text{eff}} t}{R^2} \right] \tag{9}
\]
\[ \ln MR = \ln \frac{6}{\pi} - \frac{4\pi^2 D_{\text{eff}} t}{L^2} \]  

Hence, \( D_{\text{eff}} \) can be obtained from the slope (k) of linear regression of \( \ln MR \) vs \( t \).

Thus,

\[ D_{\text{eff}} = \frac{kt^2}{4\pi^2} \]  

\( D_{\text{eff}} \) was calculated based on the assumption that the sample is spherical, so \( D_{\text{eff}} \) can be considered approximate.

### 4.5. Experiment on the Surface Crack Development.

The surface cracks are one of the fragmentation characteristics of lignite samples during drying, which are easier to observe than the internal cracks.\(^{(6,17)}\) SLP with a side length of 20 mm were selected for surface crack development experiments. The moisture transfer experiment of SLP was carried out with the equipment shown in Figure 2. The sample was taken out from the sample chamber at regular intervals, and the photos of the upper surface of SLP were collected using a high-resolution camera in a few seconds to identify the cracks. The collected surface photos were segmented from the cube sample photos and then were binarized using an appropriate gray threshold, so that the surface cracks can be clearly distinguished. The surface crack rate (CR, which can be transformed into gray images, so that the surface and then were binarized using an appropriate gray threshold, so that the surface cracks can be clearly distinguished. The surface crack rate (CR, the ratio of surface crack area to surface area determined on basis of the photos) was used to quantitatively describe the development of surface cracks.

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### References

1. Zhang, Y.; Wu, J.; Ma, J.; Wang, B.; Shang, X.; Si, C. Study on lignite dewatering by vibration mechanical thermal expression process. *Fuel Process. Technol.*, 2015, 130, 101–106.

2. Meng, X.; Zhang, G.; Chu, R.; Wu, G.; Gao, M.; Dai, J.; Bai, L. Evolution mechanism of active groups and thermal effects of Chinese lignite in low-temperature oxidation. *Chem. Eng. Commun.*, 2020, 207, 861–870.

3. Jangam, S. V.; Karthikeyan, M.; Mujumdar, A. S. A Critical Assessment of Industrial Coal Drying Technologies: Role of Energy, Emissions, Risk and Sustainability. *Drying Technol.*, 2011, 29, 395–407.

4. Liu, X.; Li, G.; Xie, R.; Zhao, Z.; Cui, P. A review on moisture re-adsorption of lignite treated using different drying techniques. *Drying Technol.*, 2021, 42, 1–15.

5. Gao, M.; Ji, P.; Miao, Z.; Wan, K.; He, Q.; Xue, S.; Pei, Z. Pore structure evolution and fractal characteristics of Zhaotong lignite during drying. *Fuel*, 2020, 267, No. 117309.

6. He, Q.; Xiao, Y.; Miao, Z.; Sun, M.; Wan, K.; Gao, M. Water Clusters in Lignite and Desorption Energy Calculation by Density Functional Theory. *ACS Omega*, 2019, 4, 14219–14225.

7. Yu, J.; Tahmasabi, A.; Han, Y.; Yin, F.; Li, X. A review on water in low rank coals: The existence, interaction with coal structure and effects on coal utilization. *Fuel Process. Technol.*, 2013, 106, 9–20.

8. Li, H.; Zhang, S.; Li, Y.; Mu, C.; Zhang, Y.; Jiang, F.; Wang, C. Numerical Simulation and Experimental Research on Drying Behavior of a Single Lignite Particle (SLP) under High-Temperature Flue Gas. *Energy Fuels*, 2017, 31, 13329–13337.

9. Wan, K.; Gao, M.; Xiao, Y.; He, Q.; Miao, Z. Modeling and analysis of lignite particle drying based on the volume averaging method. *Drying Technol.*, 2020, 1–12.

10. Barakat, A. J.; Pel, L.; Krause, O.; Adan, O. C. G. Direct observation of the moisture distribution in calcium aluminate cement and hydratable alumina-bonded castables during first-drying: An NMR study. *J. Am. Ceram. Soc.*, 2020, 103, 2101–2113.

11. Mishra, P. N.; Scheuermann, A.; Bore, T.; Li, L. Salinity effects on soil shrinkage characteristic curves of fine-grained geomaterials. *J. Rock Mech. Geotech. Eng.*, 2019, 11, 181–191.

12. Wei, C.-L.; Gao, W.-D.; Whalley, W.-R.; Li, B.-G. Shrinkage Characteristics of Lime Concretion Black Soil as Affected by Biochar Amendment. *Pedosphere*, 2018, 28, 713–725.

13. Han, Z.; Li, J.-W.; Gao, P.-F.; Huang, B.-W.; Ni, J.-P.; Wei, C.-F. Determining the Shear Strength and Permeability of Soils for Engineering of New Paddy Field Construction in a Hilly Mountainous Region of Southwestern China. *Int. J. Environ. Res. Public Health*, 2020, 17, No. 1555.

14. Zheng, S.-J.; Yao, Y.-B.; Liu, D.-M.; Cai, Y.-D.; Liu, Y. Characterizations of full-scale pore size distribution, porosity and permeability of coals: A novel methodology by nuclear magnetic resonance and fractal analysis theory. *Int. J. Coal Geol.*, 2018, 196, 148–158.

15. Senneca, O.; Urciuolo, M.; Chirone, R. A semidetailed model of primary fragmentation of coal. *Fuel*, 2013, 104, 253–261.

16. Komatsu, Y.; Sciazko, A.; Zakrzewski, M.; Kimijima, S.; Hashimoto, A.; Kaneko, S.; Szymyj, J. S. An experimental investigation on the drying kinetics of a single coarse particle of Belchatow lignite in an atmospheric superheated steam condition. *Fuel Process. Technol.*, 2015, 131, 356–369.
(17) Gao, M.; Wan, K.; Miao, Z.; He, Q.; Ji, P.; Pei, Z. Hot-air drying behavior and fragmentation characteristic of single lignite particle. *Fuel* 2019, 247, 209–216.

(18) Fu, B.-A.; Chen, M.-Q. Thin-layer drying kinetics of lignite during hot air forced convection. *Chem. Eng. Res. Des.* 2015, 102, 416–428.

(19) Kiriyama, T.; Sasaki, H.; Hashimoto, A.; Kaneko, S.; Maeda, M. Experimental observations and numerical modeling of a single coarse lignite particle dried in superheated steam. *Mater. Trans.* 2013, 54, 1725–1734.

(20) Fu, B. A.; Chen, M. Q.; Huang, Y. W.; Luo, H. F. Combined effects of additives and power levels on microwave drying performance of lignite thin layer. *Drying Technol.* 2017, 35, 227–239.

(21) Jin, L.; Li, Y.; Lin, L.; Zou, L.; Hu, H. Drying characteristic and kinetics of Huolinhe lignite in nitrogen and methane atmospheres. *Fuel* 2015, 152, 80–87.

(22) Wen, Y.; Liu, J.; Liu, X.; Wei, F.; Chang, L. Removal behaviors of moisture in raw lignite and moisturized coal and their dewatering kinetics analysis. *Drying Technol.* 2017, 35, 88–96.

(23) Tahmasebi, A.; Yu, J.; Han, Y.; Zhao, H.; Bhattacharya, S. A kinetic study of microwave and fluidized-bed drying of a Chinese lignite. *Chem. Eng. Res. Des.* 2014, 92, 54–65.

(24) Atalay, H. Performance analysis of a solar dryer integrated with the packed bed thermal energy storage (TES) system. *Energy* 2019, 172, 1037–1052.

(25) Onwude, D. I.; Hashim, N.; Abdan, K.; Janius, R.; Chen, G. Experimental studies and mathematical simulation of intermittent infrared and convective drying of sweet potato (*Ipomoea batatas* L.). *Food Bioprod. Process.* 2019, 114, 163–174.

(26) Zhao, P.-F.; Zhong, L.-P.; Zhu, R.; Zhao, Y.-M.; Luo, Z.-F.; Yang, X.-L. Drying characteristics and kinetics of Shengli lignite using different drying methods. *Energy Convers. Manage.* 2016, 120, 330–337.

(27) Wen, Y.-L.; Liao, J.-J.; Liu, X.; Wei, F.-J.; Chang, L.-P. Removal behaviors of moisture in raw lignite and moisturized coal and their dewatering kinetics analysis. *Drying Technol.* 2017, 35, 88–96.

(28) Fu, B.-A.; Chen, M.-Q.; Song, J.-J. Investigation on the microwave drying kinetics and pumping phenomenon of lignite spheres. *Appl. Therm. Eng.* 2017, 124, 371–380.

(29) Song, Z.-L.; Jing, C.-M.; Yao, L.-S.; Zhao, X.-Q.; Wang, W.-L.; Mao, Y.-P.; Ma, C.-Y. Microwave drying performance of single-particle coal slime and energy consumption analyses. *Fuel Process. Technol.* 2016, 143, 69–78.