Effect of Microwave on Drying and Moisture Reabsorption of Lignite

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Abstract: With the development of social economy and the constant consumption of energy, the reserve of high quality coal resources has shown the insufficient situation. The effective development and utilization of young lignite has become a hot issue at the present stage. However, because of its high water content and low calorific value, the further utilization of lignite is restricted greatly. Microwave drying, as a new drying technology, has great prospect in lignite drying. In this paper, the influence of microwave output power on the drying process of lignite is studied, and the energy consumption in the drying process is based on the drying process of lignite by microwave, which is related to the moisture transfer process of coal sample. In order to explore the occurrence form of moisture in coal, and discuss the reabsorption behavior of dry lignite after microwave modification.

Keywords: lignite, microwave, drying, power.

1. Introduction

Lignite is a mineral coal with the lowest degree of coalification, which is characterized by high water content, large porosity, high oxygen content and strong chemical reaction. Excessive moisture has been a major obstacle to the efficient utilization of lignite resources. There are many mature technologies at home and abroad to effectively remove moisture from lignite, but the pore structure of lignite is very developed, the specific surface area is large, and the content of oxygen functional groups is high[1-3]. Therefore, compared with other kinds of coal, lignite moisture reabsorption in humid air after drying is more significant. This article chose the Shengli lignite in Inner Mongolia, the victory of the lignite as the
research object, mainly studies the output power of microwave drying process of lignite, and simple analysis on the energy consumption in the process of drying. Based on the process of microwave drying lignite, it is related to the process of water migration in coal sample, so as to explore the occurrence form of water in coal. This paper also to the whole process of microwave drying temperature real-time measurement on the surface of the coal samples, describe the temperature change over time, to verify that the microwave drying lignite in the process of migration and changes of different types of water. Finally, it is related to the behavior of reabsorbing water from dry lignite after microwave modification.

2. Experiment
2.1 Sample Preparation
Experiments with Shengli lignite (SL), to win the first under N2 atmosphere protection to grinding and screening of coal sample, choose size range for 6 ~ 20 mesh (3.35 mm to 3.35 mm) part of experimental samples, put in brown jar, avoid light supplement. Set aside. The quality of coal sample used in each drying experiment is 5g. The results of industrial analysis and elemental analysis of coal samples used are shown in table 1.

<table>
<thead>
<tr>
<th>Proximate analysis / wt%</th>
<th>Ultimate analysis/wt%, daf</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_t</td>
<td>A_ad</td>
</tr>
<tr>
<td>29.59</td>
<td>11.96</td>
</tr>
</tbody>
</table>

*, Poor reduction results

2.2 Experiment Method
The mass is 5g and the particle size is 6-20. Shengli lignite is taken as the experimental coal sample. Using custom microwave device, the output power of 0-800 w, within the scope of the selected 240 w, 400 w, 560 w and 720 w four output power to the experiment of microwave drying lignite, continuous ventilation with N2 as protection gas in the experiment.

3. Results and discussion
3.1 Effect of Microwave Output Power on Water Removal Efficiency of Lignite
Fig.1 shows the water removal efficiency curve of coal sample under different microwave output power. As can be seen from the figure, the influence of microwave power on the drying efficiency of coal sample is very significant. Under the low power of 240w, microwave drying has no obvious effect of lignite, moisture removal efficiency with the extension of time basic remains the same, the surface temperature of coal
samples under this power also basic did not change; Along with the increase of microwave power, coal moisture removal efficiency increased gradually, when the microwave output power is 400w, the drying time of 12 min conditions, coal samples of water removal efficiency is about 50%, when the microwave output power 720w, under the same drying time, almost completely removing the moisture in coal; When the 560w power under the condition of coal moisture removal in full, under the condition of microwave output power is 400 w lignite only the moisture removal efficiency of 65%, can be seen as power has increased, dry also has a special significant efficiency increases, according to the principle of microwave heating, microwave moisture in the dry coal, need to absorb microwave energy to complete, the output power of microwave, the greater the energy per unit time is, the more water is more likely to be removed, also greatly improve drying efficiency.

![Drying efficiency curves of lignite using various microwave powers](image)

Fig.1 Drying efficiency curves of lignite using various microwave powers

Fig.2 shows the curve of lignite drying rate at different power. With the increase of microwave output power, drying rate increase distinctly, in under the condition of power is 560 w and 720 w, the drying rate of lignite are peaked at about 2 min, and 400 w, the maximum when the 4 min. Lignite dehydration of the initial stage, there is a short preheating process, this phase of the microwave energy is mainly used to heat the water inside the lignite, and coal sample itself to absorb microwave energy is less, so the moisture removal under low microwave power volume is small[3]. With the improvement of microwave power and the shortening of preheating period, lignite drying will rapidly enter the constant speed drying stage, during which microwave can be used to vaporize water.

This stage will produce a great pressure gradient to promote the migration of water vapor mixture, which is the main process of lignite drying and dehydration. At constant speed drying stage, 400w, 560w and 720w power under the moisture removal rate can reach the maximum, 0.06g/min, 0.16g/min and 0.20g/min, shows that with the
increase of output power, reduced drying preheating time, dehydration can more quickly into the constant speed drying section, dehydration rate is becoming more and more big.

![Drying rate curves of lignite using various microwave powers](image)

**Fig.2** Drying rate curves of lignite using various microwave powers

Fig.3 shows the variation curve of lignite drying rate with its drying efficiency at different power levels. It can be seen that the drying rate of three power under the condition of lignite are basically reached the maximum after take off 20% water, when drying by the constant speed drying stage into the falling rate drying stages, the moisture content of coal samples were at about 50%, this time is the main removal of lignite in a large number of free water surface, this part of the free water is attached by means of physical adsorption in the surface and the big hole in the coal samples, is relatively easy removal, suggesting that lignite critical moisture content under the influence of microwave power is not obvious, but mainly related to material itself nature and structure[4]. It is important to note that after drying to the falling rate drying stages, the moisture in coal less and less, most of the rest of the coal structure in the water, in this part of the water and coal force is bigger, it is difficult to removal, the microwave energy is mainly used for heating the ontology of coal, the utilization of microwave energy drops greatly, leading to the rest of the water after a long time is needed to heat escape, if improper operation is very easy to cause lignite temperature is too high and volatile loss, even make it happen the phenomenon of spontaneous combustion.
3.2 Changes in Surface Temperature of Lignite During Microwave Drying

In the experiment of microwave drying lignite, the microwave output power is 400 W, 560 W and 720 W condition, the determination of surface temperature change over time of lignite, the temperature change curve as shown in Fig. 4. It can be seen from the figure that the higher the microwave power, the faster the temperature rise rate of coal sample surface. Under the high power of 560 W and 720 W, coal sample temperature can be raised to above 90°C within 2 min, close to the boiling point of water. At 400 W power, it takes 4 min to reach the same temperature. The temperature variation of lignite under microwave drying is mainly divided into three stages. First stage for the preheating stage, this stage is mainly the water in coal samples due to the absorption of microwave energy to heat up, and the heat transfer process with coal sample body, then the temperature constant at about 100°C for a period of time, the corresponding to the second stage of the lignite drying constant rate drying period. After entering the constant speed drying section, continue to absorb microwave energy of coal samples, the internal vapor pressure increases rapidly, both inside and outside differential pressure is bigger, prompting seepage flow, this section of the coal sample surface temperature at about 100°C, the temperature is the boiling point of water, the large amount of free water in the lignite was out, dehydration rate was also significantly increased[5-7]. When the water content of coal sample decreases to a certain critical value (free water is basically removed), it enters the third drying stage -- deceleration drying stage. Then less and less, the moisture content in lignite and the moisture of form is basic it is difficult to emerge the internal structure of the water, so we need more energy to emerge, so coal samples absorb microwave energy efficiency is dramatically reduced, microwave energy losses increase, dehydration rate,
the temperature rise again.

![Fig.4 Temperature change curves in microwave drying](image)

Fig.4 Temperature change curves in microwave drying

Fig.5 shows the relationship between the water removal efficiency of lignite and the surface temperature of coal sample. Although three powers under the condition of coal sample surface temperature reaches 100 °C time is different, but they are in the same moisture removal rate (20%) had reached the boiling point of water, and when the moisture removal rate over 50%, the surface temperature of coal samples and start rising again. This shows that the change of power has no obvious influence on the occurrence form of various moisture in lignite.

![Fig.5 Change curves of dewatered efficiency with temperature on the surface of lignite in microwave drying](image)

Fig.5 Change curves of dewatered efficiency with temperature on the surface of lignite in microwave drying

3.3 Analysis of Energy Consumption of Microwave Drying Lignite
Microwave, as a new heating source, has a significant advantage over conventional drying methods by virtue of its unique drying principle. However, one of the important
reasons why microwave drying has not been popularized is its energy consumption. The effects of irradiation time and microwave power on microwave energy were studied.

The actual electromagnetic energies $E$, $J$, and $E_1$ and $J$ consumed in the process of microwave photometry are calculated as follows:

$$E = Pt$$  \hspace{1cm} (1)

$$E_1 = \Delta m \left(C \Delta T + Q\right)$$  \hspace{1cm} (2)

Where: $P$ is the microwave power, w; $T$ is microwave irradiation time, s; $\text{Protem}$ is the quality of removing water when dry, g; $C$ is the heat capacity of the water, 4.18 J/(g.°C); $\Delta T$ as the temperature changes in the value in the process of drying, °C; $Q$ is the latent heat of vaporization required for 1g of water, 2254.2j.

$E_1/E$ can be regarded as the utilization rate of microwave energy. The higher the ratio is, the higher the utilization rate of microwave energy is, and the lower the loss of microwave drying is[8-9].

### 3.3.1 Influence of irradiation time on microwave utilization rate

**Table 2** Effect of irradiation time on utilization of microwave energy

<table>
<thead>
<tr>
<th>Microwave time(min)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency(%)</td>
<td>40.35</td>
<td>56.61</td>
<td>58.27</td>
<td>55.04</td>
<td>51.54</td>
</tr>
</tbody>
</table>

Table 2 shows the utilization rate of microwave energy at different time of microwave radiation when the output power of microwave is 560W. In the experiment, the dehydration rate of lignite was 8.85% and the energy utilization efficiency was 40.35% after 1min microwave radiation. At 2min microwave radiation, the dehydration rate was 8.85% and the energy utilization efficiency was 56.61%. The dehydration rate was 8.85% and the energy utilization efficiency was 58.27%. The dehydration rate was 8.85% and the energy utilization efficiency was 55.04%. The dehydration rate was 8.85% and the energy utilization efficiency was 51.54% when microwave radiation was 5min. It can be seen that the use of microwave energy efficiency reach maximum at the time of 3 min 58.27%, slightly lower after, this is because a large number of water molecules to escape from the coal particle surface, after dry process into the falling rate drying stages, lignite in other forms in the occurrence of water (water) structure to escape when there is a big resistance, more energy is needed to moisture removal of this part, so the wastage of the microwave energy will rise accordingly.

### 3.3.2 Influence of microwave power and dehydration rate on microwave utilization rate

As shown in table 3, when the dehydration rate of lignite and the output power of
microwave are different, the utilization rate of microwave energy will also be different. At each power, when the dehydration rate reaches 50%, the microwave energy utilization rate is relatively high and the microwave loss is small. This phase microwave can be attached to the surface of lignite and the surface of the large and medium hole free moisture migration to provide energy, this part of the water mainly occur in the form of physical adsorption on the surface of lignite, only the van der Waals force between water coal moisture migration can be realized and discharge, needs less energy, so relatively easy removal[10]. However, after this stage, the utilization rate of microwave energy decreases significantly with the increase of water removal rate, especially when 25% of water is removed. This is because at this stage the main removal is the internal structure of the water in lignite, compact connection, this part of the water and coal damage in which the structure of the need to provide more energy, and this time the moisture in coal is less and less, is not conducive to absorb microwave energy.

Table 3 Effect of microwave power on utilization of microwave energy in different drying stage

<table>
<thead>
<tr>
<th>Dehydration rate(%)</th>
<th>Energy efficiency(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400W</td>
</tr>
<tr>
<td>25</td>
<td>30.1</td>
</tr>
<tr>
<td>50</td>
<td>29.18</td>
</tr>
<tr>
<td>75</td>
<td>19.26</td>
</tr>
<tr>
<td>100</td>
<td>14.27</td>
</tr>
</tbody>
</table>

When the dehydration rate is the same, the microwave energy utilization rate at low power (400W) is far lower than that at high power, either in the constant speed drying stage or the descending speed drying stage. So the loss of microwave energy is greater at low power.

3.4 Effects of Microwave Modification on Water Resorption of Lignite
Under the condition of 560W microwave output power, after the lignite is dried for 6min, the water content of the coal sample is reduced to 71% before the drying. By calculation, the water content of each gram of drying base is 0.0725g. Choose the way of hot gas drying the same conditions of raw coal dry to the same moisture content. Will receive two dry to the same degree of coal sample as the sample of the contrast experiment, at 120 h in the air at the same time, during the fixed time after testing the moisture absorption, the data is shown in fig.3. As can be seen in Fig.6,
within 24h, the moisture resorption amount of both dry coal samples increases. And after 24 hours, it's basically balanced. After reabsorbing water, the moisture content of coal sample obtained by hot air drying increased from 0.0725g to 0.1437g, while that of coal sample obtained by microwave drying only increased to 0.1134g. Therefore, under the same initial moisture content, microwave drying and hot air drying, compared the amount of smoking coal sample is low, it also preliminarily verified the microwave drying lignite after moisture absorption behavior has obvious inhibitory effect.

![Graph showing moisture content over re-adsorption time for microwave and hot air drying](image)

**Fig.6** The re-adsorption in the air of lignite dried by microwave and hot air

### 4. Conclusion

1. Low power microwave (240W) has no obvious effect on the drying of lignite, and its quality remains basically unchanged. With the improvement of microwave power, the dewatering efficiency and drying rate of lignite are improved significantly. Microwave drying lignite can be divided into preheating stage, constant speed drying stage and falling speed drying stage. Most of the free water on the surface was removed in the first two stages, while the structural water in the down-rate drying section was mainly removed from lignite.

2. Similar to the three stages of microwave drying lignite, the change of surface temperature of lignite during microwave drying can be divided into three stages. First stage temperature rising, and close to 100 °C, the second phase will continue to maintain a temperature of 100 °C near, this is because when the temperature reached the boiling point of water, a large number of free water removal at this stage. After the free water was basically removed, the temperature continued to rise again in the third stage.
(3) As the time of microwave irradiation continues to increase, the utilization rate of microwave energy first increases and then decreases. The maximum utilization rate of microwave energy reaches when the irradiation time is 3min. With the increase of microwave power, the energy consumption of microwave dewatering lignite decreased. (4) Compared with conventional hot gas drying, the resorption capacity of lignite after microwave modification was well inhibited.

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References