Research Article

Enhancement of Coal Permeability Using Aqueous NaCl with Microwave Irradiation

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Water in coal pores can generate strong steam explosions when treated with microwave irradiation. In order to improve the sensitivity of coal reservoirs to microwaves, we used varying concentrations of NaCl on the pore solution, which further increased the effect of microwaves on permeability enhancement. In our experiments, we selected 3 ratios of water content and 5 different concentrations of NaCl. The changes of coal water content and permeability before and after irradiation were compared. In addition, changes in coal surface temperature and internal thermal power were analyzed through thermal imaging and random sphere numerical modeling. Results showed that the increase of the proportion of solution mass and the ion concentration in the solution improved the overall dielectric properties of coal rock samples. After microwave irradiation, the average reduction rate of water content in coal rock samples increased with the increase of ion concentration in the solution. Both the average surface temperature of the coal rock samples and the average electromagnetic heating power gradually increased; this increases the temperature rise rate and maximum temperature of coal rock samples under the same irradiation time, which is conducive to better rapid accumulation of steam pressure, thereby improving the pore structure more effectively. Finally, the maximum growth rate of permeability reached 466.18%. This work provides a novel train of thought to enhance coal permeability by using microwave irradiation.

1. Introduction

Recent development of clean energy technologies, the impact of Covid-19, and the significant reduction in coal demand by OECD countries have resulted in reduction in global coal consumption. In 2019, consumption decrease was of 0.6%. In addition, its share of primary energy reached the lowest level in 16 years (27%) [1]. The International Energy Agency (IEA) also predicted that the use of coal will continue to decline in the future [2]. Nevertheless, 3.90 billion tons of standard coal were produced in China in 2020. Thus, coal still plays a dominant role in China's primary energy structure [3], accounting for about 60% [4]. In coal underground mineral deposits, the working faces gradually shift to the deeper part of the formation as mining opera-

tions progress to deeper levels. Also, coal and gas explosions may cause serious injuries to the personnel [5], events that are especially catastrophic [6]. In coal mines, gas has become an important factor restricting the efficiency of mining activities [7, 8]. At the same time, coalbed methane is an efficient and clean energy [9]. The estimated amount of China's shallow coalbed methane resources at 2000 meters and above is 36.81 trillion cubic meters. Therefore, it is likely that the exploitation of coalbed methane will be safe and of great energy benefit [10, 11].

Enhancement of coal seam permeability is generally carried out by hydraulic fracturing [12, 13]. In the case of Xinjiang, China, there is a reduced water supply [14] as well as arid and semiarid [15, 16] environments. Therefore, there is an urgent need for new options that enhance the

FIGURE 1: Explosion of water vapor contained in coal rocks after microwave heating.

FIGURE 2: Determination of saturated moisture content of coal rock (Jiangsu Kexi Instrument Co., Ltd. HH-XMTD203 water bath, temperature 20°C).

permeability of coal reservoirs. Multiple studies have shown that microwave can effectively increase the porosity and permeability of coal reservoirs [17–19]. It has also been determined that high-pressure water vapor (microwave frequency 2.45 GHz, microwave power 1 kW, irradiation time 240 s, coal sample temperature 222°C, relative atmospheric pressure 1.54 kPa) in the pore structure may cause pore deformation, destruction, and interconnection [20, 21]. The moisture present in the coal reservoir displays a dielectric loss greater than that in the coal matrix; therefore, it may be selectively heated using microwaves [22–24]. We have also previously shown that the water contained in coal rocks can be quickly heated under microwave irradiation. The water vapor that is formed in this process exerts a high

pressure on the inner wall of the pores, eventually destroying the pore structure and increasing the connectivity [25]. Figure 1 displays the macro- and microprocesses of explosion caused by water vapor contained in the coal; of course, in the process of microwave heating, the cracks in the coal are not only caused by steam pressure but also caused by the imbalance of the thermal stress, the thermal decomposition of natural filler, and so on.

Coal, a porous medium, displays a limited water storage capacity, as shown in Figure 2; with the extension of constant temperature water bath time, the water content of the three groups of coal rock samples increased more and more slowly and finally reached the upper limit of their own water storage. Therefore, there is always an upper limit to increase

TABLE 1: Experimental design.

NaCl concentration, P_k (g/L) Moisture content, Q_j (%)	$Q_1 = 2$	$Q_2 = 4$	$Q_3 = 6$
$P_1 = 0$	1	1	1
$P_2 = 16$	1	1	1
$P_3 = 32$	1	1	1
$P_4 = 48$	1	1	1
$P_5 = 64$	1	1	1

the permeability under microwave irradiation by increasing the water content of coal. Previous studies have demonstrated that microwaves are more efficiently absorbed in solutions containing ions [26]. Microwave frequency dipole polarization is considered the most important conversion mechanism for microwave heating [27]. Once the solution containing ions is placed in the microwave field, the ions follow the alternating electric field and move rapidly and repeatedly in changing directions [28]. The migration of ions forms a current that is lost as thermal energy. Therefore, the introduction of ions in the water can significantly improve its microwave absorption performance.

Pickles et al. [29] studied the influence of magnetite on the kinetics of microwave drying of low-order bituminous coal. Results indicated that the addition of magnetite as absorbent improved the process of microwave drying. Wang et al. [30] used microwave heating for the pyrolysis of lignite. These researchers demonstrated that, in the absence of additives, the temperature of lignite only reached about 200°C after irradiation with a microwave power of 700 W for 10 minutes. In contrast, the temperature of lignite significantly increased when ferroferric oxide was used as absorbent. In this case, the temperature of the sample reached 800°C after 3 minutes of irradiation at the same microwave power. Zhou [31] found out that, when a 2.34% NaCl solution was added to coal, the dielectric constant of this material rapidly increased. As a consequence, the conversion efficiency of microwave irradiation into heat was enhanced in 64%. Based on these data, we consider increasing the ion concentration of the aqueous solution present in coal in order to improve its ability to absorb microwaves. The purpose of the present research was to investigate the influence of the increase of ion mass ratio and ion concentration on coal permeability when this material was exposed to microwave irradiation. We used physical and numerical experiments in order to clarify the mechanism of permeability improvement when microwave steam explosion is used.

2. Experimental Procedure

The experimental design (Table 1) consisted of 15 different experimental conditions. Moisture content values were 2%, 4%, and 6%, and NaCl concentrations of 0 g/L, 16 g/L, 32 g/L, 48 g/L, and 64 g/L were selected with only one replicate per condition. The changes of physical parameters (including coal permeability, water content, surface temperature,

and internal temperature) of the samples before and after microwave irradiation were analyzed and compared.

Experiments consisted of two parts where coal permeability was measured before (Part I) and after (Part II) microwave irradiation under different conditions. The first step was to weigh the mass of the coal rock sample M_g after it was completely dried. The second step was to determine the initial permeability of the coal sample before microwave irradiation k_q . The third step was to obtain the maximum moisture content of the coal sample ω_i . In the fourth step, NaCl aqueous solutions with different concentrations were prepared and coal samples were soaked until saturation and air-dried until proper moisture content was achieved. The fifth step was to carry out the microwave irradiation treatment and record the temperature afterwards. The sixth step was to test and obtain the permeability of the coal sample after microwave irradiation k_{ji} . The flow chart is shown in Figure 3.

2.1. Coal Sample Preparation. Cylindrical coal samples with a diameter of 25 mm and a height of 25 mm were obtained from the Fukang mining area located in Xinjiang, China. Then, unified cylindrical coal rock samples with a height of 25 mm and a diameter of 25 mm were made. The coal rock samples were labeled with numbers 1 to 15. Materials were dried for 6 h at a temperature of 110°C using the ZK-2020 vacuum drying oven produced by Chongqing Wuhuan Test Instrument Co., Ltd. Later, inspection drying was carried out and continued for 1 hour each time. Coal samples were considered to be completely dried when the mass of the coal sample was reduced by no more than 2% after two consecutive dryings. The weighing record of mass M_g is shown in Table 2.

2.2. Pore Parameter Measurements. In order to determine the permeability of the dried coal rock samples, we used the AP-608 overburden porosity-permeability tester developed by Coretest, an American rock core experiment system company. The confining pressure during the test was set to 500 PSI (3.4475 MPa), the osmotic pressure was set to 200 PSI (1.379 MPa), the test gas was high-purity nitrogen, and the transient method was used for measurement. Table 3 displays the basic permeability parameters k_q of coal rock samples before microwave irradiation.

2.3. Determination of the Content of Saturated Water. Completely dried coal rock samples were placed into the HH-XMTD203 water bath (Jiangsu Kexi Instrument Co., Ltd.) for saturation with distilled water. Water temperature was set up to 20°C and the saturation time to 60 minutes. The mass of the saturated sample was recorded as M_s . After weighing, the maximum moisture content $\omega_{k,j}$ was calculated using the mass of completely dried coal rock samples M_g , as shown in the following equation.

$$\omega_{k,j} = \frac{M_s - M_g}{M_g} \times 100\%. \quad (1)$$

Because there is an upper limit on the water retention of different coal rock samples, the experiment requires that the

FIGURE 3: Permeability test flow chart.

TABLE 2: Mass (g) of completely dried coal samples.

NaCl concentration, P_k (g/L) Moisture content, Q_j (%)	$Q_1 = 2$	$Q_2 = 4$	$Q_3 = 6$
$P_1 = 0$	12.453	13.576	13.605
$P_2 = 16$	11.389	14.323	13.059
$P_3 = 32$	8.348	12.699	14.050
$P_4 = 48$	11.759	11.625	13.012
$P_5 = 64$	12.325	12.235	12.211

TABLE 3: Initial permeability (mD) of coal rock samples.

NaCl concentration, P_k (g/L) Moisture content, Q_j (%)	$Q_1 = 2$	$Q_2 = 4$	$Q_3 = 6$
$P_1 = 0$	0.9977	0.5614	0.2401
$P_2 = 16$	0.5083	0.2245	0.1625
$P_3 = 32$	0.3460	0.2225	0.1525
$P_4 = 48$	0.2344	0.1803	0.1490
$P_5 = 64$	0.2288	0.1567	0.0835

TABLE 4: Maximum moisture content (%) of coal rock samples $\omega_{k,j}$.

NaCl concentration, P_k (g/L) Moisture content, Q_j (%)	$Q_1 = 2$	$Q_2 = 4$	$Q_3 = 6$
$P_1 = 0$	9.12	9.87	9.94
$P_2 = 16$	8.86	9.26	10.43
$P_3 = 32$	10.05	9.20	10.13
$P_4 = 48$	9.18	9.98	10.86
$P_5 = 64$	9.19	9.56	10.61

TABLE 5: Time of microwave irradiation to coal rock samples (s).

NaCl concentration, P_k (g/L) Moisture content Q_j (%)	$Q_1 = 2$	$Q_2 = 4$	$Q_3 = 6$
$P_1 = 0$	29	32	32
$P_2 = 16$	27	34	31
$P_3 = 32$	20	30	33
$P_4 = 48$	28	27	31
$P_5 = 64$	29	29	29

coal rock samples can store 6% of water, so we tested the upper limit of water retention of each coal rock sample, as shown in Table 4. It is found that the upper limit of water saturation of all the coal rock samples is greater than 6%, so all coal rock samples meet the experimental requirements.

2.4. Preparation of Coal Samples Containing NaCl Solution. Dried coal samples were soaked in 50 mL of different NaCl concentrations until saturation. Later, corresponding mois-

ture content was achieved after air-drying. In general, after air-drying occurs, part of the water evaporates and the NaCl remains in the sample. As a result, NaCl concentration in the coal pores gradually increases, resulting in a final concentration higher than the preset value. Therefore, in order to determine the NaCl mass (g) that should be added to 50 mL of water, we considered the saturated moisture content $\omega_{k,j}$ of each coal sample, the preset moisture content Q_j of the experimental scheme, and the preset NaCl

TABLE 6: Change in moisture content in coal rock samples after microwave irradiation (%).

NaCl concentration, P_k (g/L) Moisture content, Q_j (%)	$Q_1 = 2$		$Q_2 = 4$		$Q_3 = 6$		Average reduction rate
	Moisture content after microwave irradiation	Reduction rate of moisture content	Moisture content after microwave irradiation	Reduction rate of moisture content	Moisture content after microwave irradiation	Reduction rate of moisture content	
$P_1 = 0$	1.96	1.79	3.85	3.74	5.49	8.56	4.69
$P_2 = 16$	1.95	2.38	3.79	5.13	5.37	10.46	5.99
$P_3 = 32$	1.95	2.64	3.79	5.26	4.98	16.97	8.29
$P_4 = 48$	1.94	3.05	3.76	5.95	3.93	34.43	14.48
$P_5 = 64$	1.93	3.37	3.67	8.37	3.59	40.18	17.31
Average value		2.64		5.69		22.12	

concentration P_k . The formula is deduced as follows: (1) soak the coal pillar in pure water until the water is saturated and record the water saturation mass of the coal pillar as M_s ; (2) the salt added to the water is calculated as $(M_g \times Q_j) / 50 \times P_k$; (3) the mass of water that can be stored in coal rock samples is calculated as $M_s - M_g$; and (4) the formula for the mass of NaCl to be added for soaking 50 mL water of coal pillar is shown in the following equation.

$$\text{NaCl}_{50\text{ml}} = \frac{M_g \times Q_i \times P_k}{M_s - M_g}. \quad (2)$$

The calculated NaCl mass was used to prepare the corresponding NaCl aqueous solution, and the coal rock samples were soaked to reach a water-saturated state. Then, the samples were air-dried. During the drying process, when the coal sample mass reached 1.06, 1.04, and 1.02 times the value of the quality control, that is, the completely dried mass M_g , coal samples with different NaCl concentrations at moisture content of 6%, 4%, and 2% were obtained.

2.5. Determination of Microwave Irradiation Duration. Throughout its formation, coal is affected by long-term high temperature and high pressure environments, the diversity of coal-forming plants, and complex physical and chemical changes. This leads to high coal heterogeneity, and thus, the mass of each sample is slightly different. Differences in individual weight of the samples may cause variations in the absorption of microwave energy by the coal rocks. In order to eliminate these potential variations, the irradiation time was calculated using the following equation.

$$T_{i,j} = \frac{M_g}{M_A} \times 30. \quad (3)$$

For the microwave experiment, we used the Newsail commercial microwave oven. The microwave power was set to 2 kW and the microwave frequency to 2.45 GHz, and the specific duration of microwave irradiation is shown in Table 5.

After irradiation, an UTi-165A thermal imaging camera was used to take pictures and measure temperature. The

mass of the samples after irradiation was also obtained and recorded.

3. Results

3.1. Changes in Moisture Content. As shown in Table 6, the moisture content of the coal samples after microwave irradiation was lower than the initial one. Data indicated that as the initial coal moisture content increased, the reduction rate of the coal moisture after the microwave treatment also increased. The average reduction rates at initial moisture content conditions of 2%, 4%, and 6% were 2.64%, 5.69%, and 22.12%, respectively. In addition, with increasing initial NaCl concentrations in the internal coal solution, the average decrease rate of the moisture content after microwave irradiation also increased. The average reduction rate of moisture content under NaCl concentrations of 0 g/L, 16 g/L, 32 g/L, 48 g/L, and 64 g/L were 4.69%, 5.99%, 8.29%, 14.48%, and 17.31%, respectively.

3.2. Changes in Permeability. As shown in Table 7, the permeability of the coal samples after microwave irradiation increased as compared with the initial permeability. Distribution of the increase rate of permeability in each coal sample and under the same coal rock moisture content indicated that the greater the NaCl concentration, the higher the increased permeability rate after microwaving. NaCl concentrations of 0 g/L, 16 g/L, 32 g/L, 48 g/L, and 64 g/L resulted in an increase rate in average permeability of 196.37%, 216.39%, 343.51%, 465.80%, and 466.18%, correspondingly.

4. Promotion Mechanism of Ionic Solution in Microwave Irradiation of Coal Rock

The experimental test shows that the NaCl aqueous solution in coal rock samples will have a positive impact on the permeability of coal rock samples. In order to find out how NaCl aqueous solution affects the dielectric properties of coal and rock and then affects the temperature change of coal rock samples under the action of microwave, it will be discussed below.

TABLE 7: Changes in coal moisture content after microwave irradiation (%).

NaCl concentration, P_k (g/L) Moisture content, Q_j (%)	$Q_1 = 2$		$Q_2 = 4$		$Q_3 = 6$		Average growth rate
	Permeability before microwave irradiation	Permeability after microwave irradiation	Permeability before microwave irradiation	Permeability after microwave irradiation	Permeability before microwave irradiation	Permeability after microwave irradiation	
$P_1 = 0$	0.9977	2.2285	0.5614	0.8799	0.2401	1.2214	196.37%
$P_2 = 16$	0.5083	0.8216	0.2245	0.8602	0.1625	0.6571	216.39%
$P_3 = 32$	0.3460	0.5776	0.2225	1.6077	0.1525	0.6726	343.51%
$P_4 = 48$	0.2344	0.7624	0.1803	0.8572	0.1490	1.3361	465.80%
$P_5 = 64$	0.2288	0.5888	0.1567	0.7912	0.0835	0.7818	466.18%

4.1. Mechanism of the Effect of Ionic Solutions on Dielectric Properties of Coal Rocks. Coal rock is a porous medium where dielectric properties are mainly determined by the volume of air and moisture and coal matrix characteristics. Among them, the dielectric response of moisture in the microwave field far exceeds that of air and coal. This section studies the mechanism through which the proportion of solution mass and solution ion concentration affects the dielectric properties of coal.

4.1.1. Effect of Solvent to Solute Mass Ratio on Dielectric Properties of Coal Rocks. Dielectric loss and Joule heat loss occur when microwaves are irradiated on different materials. Under the action of an electric field, the polar molecules present in these materials undergo relaxation polarization and resonance polarization processes, which lead to dielectric loss. At the same time, under a given electric potential, an electric current is generated inside the dielectric material. This process causes the loss of Joule heat. These two phenomena are the key to heat generation. According to previous studies, the total electromagnetic power loss that occurs when microwaves irradiate the medium can be calculated according to the following equation:

$$P_w = 2\pi f \epsilon_w'' \epsilon_0 |E|^2, \quad (4)$$

where P_w (W/m³) is the electromagnetic loss thermal power density; f is the frequency of the electric field (Hz); ϵ_w'' is the imaginary part of the relative complex permittivity of the heated object, which characterizes the ability of the substance to absorb and lose electromagnetic field energy; $\epsilon_0 = 8.85 \times 10^{-12}$ F/m is the dielectric constant in vacuum; and $|E|$ (V/m) is the modulus of the electric field intensity.

According to Equation (4), in addition to the microwave power and microwave frequency, the factors affecting the microwave heating of a substance mainly depend on the inherent dielectric properties of the heated material. The dielectric constant is an important factor that determines the increment in temperature of coal. A significant amount of tests have been conducted to determine the dielectric constant of coal rocks. It is generally believed that the real part of the dielectric constant of the coal rock matrix is between 1.6 and 2.5, and the imaginary part of the dielectric constant is between 0.05 and 0.2 [32]. The real and imaginary values

of the dielectric water constant are much higher than those of the coal matrix, which are 80 and 9, respectively [33, 34].

Since the coal rock is a mixed substance, the imaginary part of the mixed relative complex permittivity can be estimated considering the imaginary part of the mixed relative complex permittivity and volume ratio of each substance. In general, as the moisture content increases, the overall dielectric properties of the coal rocks also increase. Under the same microwave power and irradiation time, the internal temperature of the coal rocks continuously increases. High temperatures and pressures cause the violent evaporation of water. In this processes, the greater the initial moisture content of the coal, the greater the reduction rate of the coal's moisture content after microwave irradiation (Figure 4). The higher the moisture content in the coal rocks, the greater the rate of temperature increase, the higher the temperature of the coal rock, and the higher the sources of steam. When the volume is limited, especially when the pore volume inside the coal rock is small, the pressure of the expanding gas on the inner wall of the pore increases. Since the force area does not change, the absolute vapor pressure inside the coal rock rapidly increases.

At the same time, because of its particular properties, the total porosity of coal rocks displays a maximum value. Thus, there is an upper limit on the amount of water they can hold, and in consequence, there is a certain upper limit for the overall improvement of the dielectric properties of coal samples. In order to further improve the dielectric response of water to the microwave field, it is necessary to explore the influence of ion concentration on the dielectric properties of coal rocks.

4.1.2. Effect of Ion Concentration on Dielectric Properties of Coal Rocks. As Figure 5 displays, permeability of the coal rocks increased with increasing NaCl concentrations. Outlier data occurred because of the high heterogeneity in the coal samples. Anomalies occurred because pores and fissures connected to the outside expanded and connected by means of the high water vapor pressure, causing a substantial increase in permeability. Thus, the increment in moisture content and NaCl concentration can effectively increase the permeability of coal after microwave irradiation. Compared to a completely dry coal sample, under high moisture content and high NaCl concentration, coal permeability increased 4.66 times after microwave irradiation. Under

FIGURE 4: Reduction in moisture content rate after microwave irradiation (%).

FIGURE 5: Increasing rate of coal rock permeability.

the same moisture content conditions, results indicated that by increasing the ion concentration of the solution, the average permeability increased 1.91 times in the three cases.

Adding NaCl to the solution can greatly increase the imaginary part of the complex permittivity of water, which can be calculated according to the following equation:

$$\varepsilon''_w = \frac{\omega\tau_w(\varepsilon_{w0} - \varepsilon_{w\infty})}{1 + (\omega\tau_w)^2} + \frac{\sigma}{\omega\varepsilon_0}, \quad (5)$$

where ω (Hz) corresponds to the angular frequency, f (Hz) is the frequency of the electric field, τ_w (s) is the relaxation time of water polarization, ε_{w0} (F/m) is the dielectric constant of water in an electrostatic field, $\varepsilon_{w\infty} = 4.9$ F/m represents the dielectric constant at high frequency, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the dielectric constant of vacuum, and σ (S/m) is the conductivity of water.

Equation (5) indicates that the relaxation time τ_w of the polarization of water media in the microwave field and the dielectric constant ε_{w0} of water in the electrostatic field are

FIGURE 6: τ_w and ϵ_{w0} as a function of temperature: (a) τ_w as a function of temperature; (b) ϵ_{w0} as a function of temperature.

FIGURE 7: Relationship between NaCl concentration and conductivity of the solution.

important parameters that affect the dielectric loss of water. They are functions of temperature, as seen in equations (6) and (7), as shown in Figures 6(a) and 6(b).

$$2\pi\tau_w = 1.1109 \times 10^{-10} - 3.824 \times 10^{-12}T + 6.938 \times 10^{-14}T^2 - 5.096 \times 10^{-16}T^3, \quad (6)$$

$$\epsilon_{w0} = 88.045 - 0.4147T + 6.295 \times 10^{-4}T^2 + 1.075 \times 10^{-5}T^3. \quad (7)$$

Conductivity σ , which is closely related to the ion concentration of the solution, is the most important parameter that affects Joule heat loss. The higher the electrical conductivity, the stronger the ability of the coal rock samples to absorb an electromagnetic field, and the more intense the dielectric response under the same moisture content. In the present research, NaCl was used to increase the ion concentration of water present in the coal rock samples, thereby increasing the conductivity of the aqueous solution. The concentration of NaCl and the conductivity of the solution are shown in Figure 7.

According to data shown in Figure 7, with increasing NaCl concentrations, conductivity also increased. NaCl concentrations of 0 g/L, 16 g/L, 32 g/L, 48 g/L, and 64 g/L resulted in conductivity values of 0 s/cm, 2.75 s/m, 5.2 s/m, 7.6 s/m, and 10 s/m, respectively. This increment was extremely high for NaCl-containing solutions, greatly increasing the imaginary part of the dielectric constant of water. As a result, the moisture in the coal rock samples can be heated more quickly in the microwave field, also quickly evaporating and generating the steam explosion. The release of a large amount of high temperature and high pressure steam significantly improved the pore opening, dredging, and reaming. This also shows that the addition of NaCl significantly improved coal permeability (Figure 5).

4.2. Mechanism of the Effect of Ion Concentration on Temperature Distribution in the Coal Rocks. Through the above analysis, it is found that after injecting NaCl solution, the imaginary part of the dielectric constant of water increases greatly and then increases the overall temperature of coal rock samples. Therefore, the surface temperature test and internal temperature numerical simulation of coal rock samples with different NaCl concentrations after microwave irradiation were carried out, and the specific promotion effect of NaCl solution on coal rock sample temperature and the mechanism of increasing permeability were explored.

4.2.1. Influence of Ion Concentration on Surface Temperature Distribution in Coal Rocks. The pictures taken by the UTi-165A thermal imager for temperature measurement are shown in Table 8. The average temperature of the original coal before microwave irradiation is $22.6^{\circ}C$. Figure 8 summarizes the temperature characterization of coal rock samples under 15 different conditions.

Figure 8 shows that the relationship between NaCl concentrations and temperature of the coal rocks after microwave irradiation properly fitted a linear equation. The trend basically showed a linear increase. Under the same microwave power, the average temperatures of coal rock

TABLE 8: Mapping of coal surface temperature distribution after microwave irradiation.

NaCl concentration, P_k (g/L) Moisture content Q_j (%)		$Q_1 = 2$	$Q_2 = 4$	$Q_3 = 6$
$P_1 = 0$
$P_2 = 16$
$P_3 = 32$
$P_4 = 48$
$P_5 = 64$

FIGURE 8: Surface temperature of water-bearing coal rocks after microwave treatment.

samples with of NaCl solution concentrations of 16 g/L, 32 g/L, 48 g/L, and 64 g/L were 62.5°C, 68.6°C, 73.9°C, and 82.9°C, respectively. Compared with the average temperature of 53.4°C of coal rock samples without NaCl aqueous solution, the temperature increased by 17.04%, 28.46%, 38.4%, and 55.2%, respectively.

Temperature was the most important factor that directly determined the internal pressure in coal rocks. The rapid increase in temperature presents the following benefits: (1) Extremely high temperature is conducive to large temperature gradients, especially in mixtures with complex internal components such as coal rock samples. Components of coal rocks include the coal matrix, different minerals, water, and various volatile compounds, among others. The dielectric properties of different materials also vary, which easily cause the thermal stress distribution and unevenness of the coal rock samples in the microwave field. The higher the extreme temperature, the stronger the unevenness, and the more likely to produce the tearing effect on the primary fissures inside the coal body, as well as the cracking effect of the pores. (2) Temperature increase indicates that the rate of heating of the coal body is accelerated. The rapid increase in temperature favors the rapid formation of water vapor. This means that in the same period of time, coal samples containing NaCl solutions accumulate more water vapor as compared to those where no aqueous solution are present. According to the ideal state gas equation, when other conditions are the same, the higher the amount of gas, the higher the pressure generated inside the pores. This process favors the expansion of pores and cracks. Under pressure, pores more likely transform into larger pores, and some of them maybe also broken and connected with small cracks. Independent cracks may connect with each other or with the external environment. This process greatly improves the permeability of coal rocks.

Overall temperature of coal rocks can be determined through physical analysis. However, the specific temperature

inside the coal rock cannot be measured. Therefore, in the present investigation, numerical simulation was used to study the internal changes of coal after microwave irradiation and to explore the influence of ion concentration on the internal temperature distribution.

4.2.2. The Influence of Ion Concentration on Internal Temperature Distribution in Coal Rocks. The COMSOL Multiphysics numerical analysis software was adopted for microwave heating simulation. A three-dimensional model was established according to the actual situation. The coal rock was 25 mm in diameter and 25 mm in height. In order to simulate the pores of coal, since the average porosity of 15 coal samples used in this experiment was 30%, 100 spheres were randomly arranged in the coal model material, and the volume of spheres accounted for 30% of the model volume. After calculation, the diameter of each sphere was 2.064 mm. Seven, 14, and 20 microspheres were randomly selected as water-bearing pores to simulate the coal rock with water content of 2%, 4%, and 6%, respectively. The model is shown in Figure 9. The following ideal conditions were set up during the entire simulation process: (1) The composition of coal rock did not change during the entire microwave irradiation process. (2) The thermodynamic and electrical parameters of each substance remained unchanged. (3) Both the inner wall of the microwave oven and the waveguide were considered perfect magnetic conductors. (4) Only the influence of the proportion of aqueous solution and ion concentration on coal temperature was considered; on the other hand, we did not consider the influence of radiative and convective heat transfers on coal temperature.

The maximum body temperature of coal rock samples was extracted in the microwave heating simulation, and the results are shown in Figure 10. As observed, the maximum body temperature of coal rock samples after microwave irradiation also increases with the increase of ion concentration of the NaCl solution, and the internal temperature is greater than the surface temperature. However, different from the above, the maximum surface temperature of coal rock samples measured in the physical experiment basically increases linearly with the increase of ion concentration of the NaCl solution, while the increase rate of the maximum body temperature of coal samples in the simulation becomes slower and slower with the increase of ion concentration of the NaCl solution. This is closely related to the penetration depth of the microwave to the coal rock samples.

When the microwave enters the medium, the medium absorbs the microwave energy and converts it into heat energy. The field strength of microwave decreases continuously with the increase of the depth of the incident medium. The depth reflects the penetration ability of the microwave in the medium. When the microwave enters the coal sample, the surface energy density of the coal rock sample becomes the largest, and its energy decreases exponentially with the penetration of the microwave into the coal rock sample. In order to characterize the attenuation ability of the material to the microwave power, the microwave penetration depth (d_p) is employed, which is defined as the distance when the

FIGURE 9: Surface temperature of water-bearing coal rock after microwave treatment: (a) microwave oven; (b) three-dimensional numerical model; (c) random sphere numerical model.

microwave power is reduced from the surface value of the medium to the surface value e^{-1} (about 36.79%) [35]:

$$d_p = \frac{c_0}{2\sqrt{2}\pi f \sqrt{\epsilon' \left[\sqrt{1 + \left(\epsilon''/\epsilon' \right)^2} - 1 \right]}}, \quad (8)$$

where C_0 is the speed of light, in m/s; f is the microwave frequency; ϵ' represents the real part of the dielectric constant; and ϵ'' is the imaginary part of the dielectric constant. In this study, for the coal rock with the same moisture content, the real part of the dielectric constant of coal samples is basically unchanged. According to equation (5), the addition of the NaCl solution only greatly improves the imaginary part of the dielectric constant. According to equation (8), with the

increase of the imaginary part of the dielectric constant, the overall microwave penetration depth of coal samples will be smaller and smaller. Therefore, under microwave irradiation, the attenuation loss of medium on the surface of coal samples is the smallest, and the energy density of microwave is the largest. The basic temperature curve of coal rock sample surface presents a linear growth trend. With the increase of ion concentration of the NaCl solution, the overall microwave penetration depth of coal samples decreases, resulting in a gradual decline of the rise rate of the maximum body temperature of coal rock samples.

In order to clarify the absorption of microwave energy in different positions of coal rock samples, the dielectric loss power density P_d (in W/m^3) of different spatial positions was extracted in the microwave heating simulation. This parameter is used to express the microwave energy absorbed

FIGURE 10: Simulation of maximum body temperature of coal rock samples.

FIGURE 11: Numerical simulation results.

per unit volume in unit time at any spatial position (position z) inside the dielectric material.

As shown in Figure 11, it can be seen that in the longitudinal direction the water content increases continuously at the same NaCl concentration; in the transverse direction, the NaCl concentration increases at the same horizontal water content. Whether horizontal or vertical, the temperature of coal samples is getting higher and higher, and the area of high temperature is getting larger and larger (see the light white part of the simulated coal pillar). The average power density of dielectric loss in coal samples under different conditions is arranged as shown in Figure 11. As observed, the average power density of dielectric loss in coal samples increases with the increase of NaCl concentration,

which is consistent with the maximum temperature inside the coal samples.

The dielectric loss power density P_d can be expressed as [36]

$$P_d(z) = \frac{\omega}{c} \frac{4\epsilon'' S_0 e^{-2\alpha z}}{\sqrt{\epsilon'^2 + \epsilon''^2} + \sqrt{2(\sqrt{\epsilon'^2 + \epsilon''^2} + \epsilon') + 1}}, \quad (9)$$

where S_0 corresponds to the average energy flow density of the microwave generator and is determined by the microwave power. According to the equation, the average power density P_d of dielectric loss of coal rock samples under the

same irradiation condition is mainly determined by the imaginary part of the relative dielectric constant of the medium. In this study, under the condition of constant water content and with the increase of NaCl concentration, the real part of the dielectric constant is basically unchanged, while the imaginary part increases greatly, which leads to the increase of the overall dielectric loss power density of the coal sample; that is, the coal samples absorb more and more microwave energy in unit time, which effectively improves the overall temperature of the coal samples.

As suggested by combination of the penetration depth d_p and the average power density P_d of the dielectric loss, firstly, the addition of the NaCl solution can improve the dielectric response of coal rock samples in the microwave field, so that the coal rock can absorb more energy and produce higher temperature in unit time, which helps to generate greater steam pressure and promote the expansion of original pores and fissures, and may generate new fissures. Meanwhile, with the increase of the NaCl concentration, the penetration depth decreases, this may lead to the thermal stress distribution inside and outside the coal rock becoming more uneven, the original mechanical equilibrium field inside the coal rock may be broken, new fissures are produced, and the original pores/fissures will also develop and connect under the effect of internal steam pressure, which may improve the conditions of pores and fissures and enhance the overall permeability of coal rock samples.

5. Conclusions

- (1) As the mass proportion of the ionic solution increased, the overall dielectric properties of the coal rock samples increased. In addition, the average decrease rate of the moisture content after microwave irradiation also increased. These results showed that more water was involved in the steam explosion
- (2) The increase of NaCl aqueous solution concentration reduces the penetration ability of the microwave in the coal rock sample, so more energy will be concentrated on the surface of sample, which is well proven by the thermal imaging temperature test. The test result indicates that the average surface temperature of coal samples at four different concentrations of NaCl increased by 17.04%, 28.46%, 38.4%, and 55.2% as compared with those samples without NaCl. At the same time, the NaCl aqueous solution enhances the overall microwave absorption capacity of coal samples, which is well proven by the maximum temperature and dielectric loss thermal power density of samples in numerical analysis. As observed, the average power density of dielectric loss in coal samples increases with the increase of NaCl concentration; this change trend is consistent with the maximum temperature inside the coal samples
- (3) Both physical and numerical experiments show that the NaCl solution can effectively enhance the temperature of coal rock samples with microwave irradiation.

Higher temperature will make it more possible to increase the steam pressure in the pores, which may be more conducive to the connection and expansion of the pores. It should be pointed out that the increase of steam pressure is not the only reason for the microcracking process, but it is a favorable factor

- (4) As the concentration of the ionic solution increased, the average growth rate of the overall permeability was 196.37%, 216.39%, 343.51%, 465.80%, and 466.18%. At a same moisture content, increasing NaCl concentration enhanced permeability 1.91 times

Data Availability

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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