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Research Article

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Numerical Simulation of Coal Seam Gas Migration Response Characteristics under Different Microwave Frequencies

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Abstract Microwave heat injection is an effective means to improve the efficiency of gas extraction. Microwave frequency has a significant influence on microwave performance, but few studies focused on the selection of microwave frequency suitable for gas migration in coal seam. In this study, an electromagnetic-thermal-fluid-solid coupling model of microwave heat injection is established, and the coal seam gas migration law under the four industrial microwave frequencies of 433 MHz, 915 MHz, 2450 MHz and 5800 MHz is simulated. The evolution law of electric field intensity, coal seam temperature, permeability ratio, gas content, cumulative gas extraction amount and gas extraction rate in the process of gas extraction is compared and analyzed. The results show that the temperature of coal seam increases rapidly in the microwave penetration area and then transfers to the low temperature area. The heat injection effect of 915 MHz microwave is the best, and that of 5800 MHz microwave is the worst, and 915 MHz microwave penetration zone is 10 times that of 5800 MHz. Microwave heat injection extraction can improve the permeability of coal seam and promote gas adsorption and desorption. The cumulative gas extraction amount of 915 MHz microwave on the 300th day was 919 m^3, and the maximum gas extraction rate reached 26.37 m^3/d.

Keywords microwave frequency, gas extraction, electromagnetic-thermal-fluid-solid coupling, gas migration law, numerical simulation

1. Introduction

Coal seam gas extraction can reduce the occurrence of gas disasters, develop and utilize gas reasonably, but also reduce greenhouse gas emissions, improve energy structure, and ensure national energy security. Microwave thermal injection mining has been regarded as a more advantageous method to enhance gas extraction.Microwave radiation uses the principle of medium loss to heat the material, and the minerals in coal will produce thermal effect under the action of electromagnetic wave [1-3], so as to achieve the purpose of changing the structure of coal [4]. Fu et al. [5] studied the effects of microwave radiation on the physical and chemical properties and methane adsorption and desorption capacity of four kinds of coal. Wang et al. [6] conducted methane desorption experiments with real time microwave loading and without real time microwave loading, and found that real time microwave loading could significantly improve coalbed methane productivity. Ali et al. [7] used Maxwell equations and coupled heat and mass transfer to simulate electromagnetic field and heat radiation in coal and coal in a 2450 MHz microwave system, and gave the temperature distribution inside the coal. In terms of coal seam gas extraction by microwave heat injection, Ma et al. [8] discussed the relationship between different microwave power, different irradiation time, different energy input and coal permeability at 2450 MHz microwave frequency by using the seepage experiment system of coal containing gas under microwave radiation.

In order to explore the optimum frequency of the interaction between microwave and coal reservoir, the electromagnetic-thermal-fluid-solid coupling model was established, and the evolution law of electric field intensity, coal seam temperature, permeability ratio, gas content, cumulative gas extraction and gas extraction rate under different microwave frequencies was simulated and compared by COMSOL Multiphysics numerical software. To provide reference for coal seam gas extraction by microwave heat injection.

2 Model of coal seam gas extraction by microwave heat injection

2.1 Basic assumption

In order to simplify the calculation process, the mathematical model of coal seam gas extraction by microwave heat injection is assumed as follows:

(1) The coal matrix is uniform and homogenous.

(2) The gas in the coal seam is the ideal gas.

(3) Gas seepage conforms to Darcy's law.

(4) Gas adsorption and desorption conform to Langmuir equation.

2.2 Electromagnetic-thermal-fluid-solid coupling model

(1) Governing equation of electromagnetic field

The Maxwell equations are simplified to Helmholtz vector equations [9]:

$$\nabla \times \mu_r^{-1}(\nabla \times \boldsymbol{E}) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)\boldsymbol{E} = 0 \tag{1}$$

where μ_r is the relative permeability (N/A^2), ε_r is the relative permittivity, σ is the conductivity (S/m), k_0 is the wave number in free space, ω is the angular frequency (rad/s), ε_0 is the dielectric constant of the vacuum (F/m), $\boldsymbol{E}$ is electric field intensity (V/cm).

(2) Governing equation of temperature field

Taking the electromagnetic loss power as the heat source of the heat transfer equation, the electromagnetic and thermal coupling equation can be obtained:

$$\rho_c C_p \frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + \frac{1}{2}\left[R_e(\boldsymbol{J} \cdot \boldsymbol{E}^*) + R_e(i\omega \boldsymbol{B} \cdot \boldsymbol{H}^*)\right] \tag{2}$$

where ρ_c is the coal body density (kg/m^3), C_p is the constant pressure heat capacity of coal (J/(kg·K)), T is the temperature of coal body, k is thermal conductivity (W/(m·K)), R_e represents the real part, $\boldsymbol{J}$ is current density (A/m^2), $\boldsymbol{B}$ is magnetic flux density (Wb/m^2), $\boldsymbol{H}$ is magnetic field intensity (A/m).

(3) Governing equation of stress field

The modified Navier equation for coal deformation is expressed as:

$$Gu_{i,jj} + \frac{G}{1-2\upsilon}u_{j,ji} - \alpha p_{,i} - K\alpha_T T_{,i} - K\varepsilon_{s,i} + f_i = 0 \tag{3}$$

where G is the shear modulus of coal body (Pa), v is Poisson's ratio, K is the bulk modulus of coal body (Pa), α is the Biot coefficient of coal body, α_T is the thermal expansion coefficient of coal (1/K), f_i is the volume stress in all directions (Pa).

(4) Governing equation of seepage field

The porosity equation and permeability equation of coal can be expressed as:

$$\varphi = 1 - \frac{1-\varphi_0}{1+\varepsilon_v}\left(1 - \alpha_T \Delta T - \frac{\Delta p}{K_s}\right) \tag{4}$$

$$k = \frac{k_0}{\varphi_0^3}\left[1 - \frac{1-\varphi_0}{1+\varepsilon_v}\left(1 - \alpha_T \Delta T - \frac{\Delta p}{K_s}\right)\right]^3 \tag{5}$$

Adsorbed gas content can be expressed as [10]:

$$V_s = \frac{V_L p}{p + P_L}\exp\left[-\frac{c_2}{1+c_1 p}(T - T_r)\right] \tag{6}$$

The seepage field equation is expressed as:

$$\frac{\partial}{\partial t}\left[\varphi \frac{M_g p}{RT} + (1-\varphi)\rho_{gs}\rho_c V_s\right] + \nabla \cdot \left(-\frac{M_g p}{RT} \cdot \frac{k}{\mu} \nabla p\right) = Q_m \tag{7}$$

where ε_v is the total volume strain variation, φ_0 is the initial porosity of coal seam, k_0 is the initial permeability of the coal seam (m^2), K_s is coal matrix volume modulus (Pa), V_L is Langmuir volume constant (m^3/kg), P_L is Langmuir pressure constant (Pa), c_1 is Langmuir pressure correction coefficient (MPa^{-1}), c_2 is Langmuir volume correction coefficient (K^{-1}), and T_r is the reference temperature of gas adsorption experiment (K), M_g is the molar mass of methane gas (kg/mol), R is the universal gas constant (J/mol/K), ρ_{gs} is the gas density under standard conditions (kg/m^3), k is the permeability of coal (m^2), and μ is the dynamic viscosity coefficient of gas (Pa·s).

2.3 Geometric model and boundary conditions

A two-dimensional geometric model of coal seam gas extraction by microwave heat injection was established, as shown in Figure 1. The range of microwave heat injection gas extraction was 10 m × 10 m × 1 m, the diameter of gas extraction hole was 98 mm, and microwave sources were located on both sides of the model. It is assumed that the initial temperature of coal seam is 300 K, the initial gas pressure is 1.5 MPa, and the negative extraction pressure is 15 kPa. Set measuring line EF and monitoring points A (0.5 m, 0), B (2.5 m, 0) and C (4.5 m, 0). The grid was divided using a free triangular grid automatically divided according to the physical field, as shown in Figure 2. Table 1 shows parameter Settings of the model.

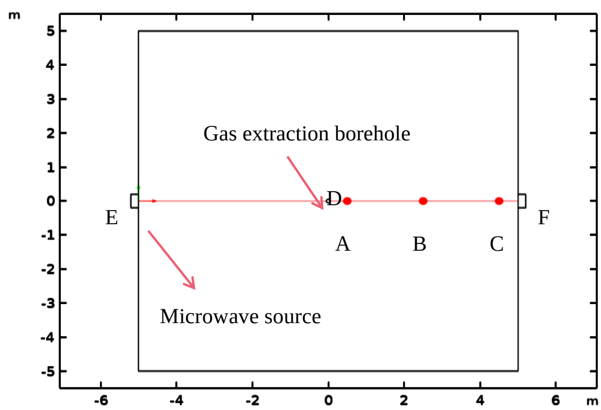


Figure 1: Geometric model

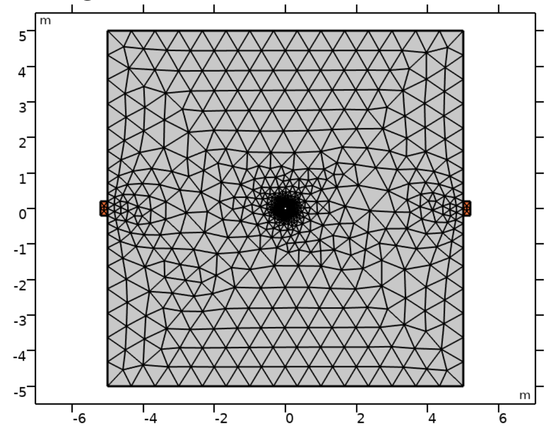


Figure 2: Grid division

Table 1: Parameter settings

Parameters	Value	Parameters	Value
Microwave power, p	100 W	Universal gas constant, R	8.314 J/(mol·K)
Permittivity of coal, ε'	2.53	Gas dynamic viscosity coefficient, μ	1.84×10^{-5} kg/m^3

Loss coefficient of coal, ε''	0.2	Methane gas molar mass, M_g	16 g/mol
The conductivity of coal, σ	0.02 S/m	Coal matrix volume modulus, K_s	7979 MPa
Coal body density, ρ_c	1250 kg/m^3	Initial porosity of coal seam, φ_0	0.045
Young's modulus of coal, E	2713 MPa	Initial permeability of coal seam, k_0	2.5×10^{-16} m^2
Thermal conductivity of coal, k	0.478 W/(m·K)	Langmuir volume constant, V_L	0.043 m^3/kg
Poisson's ratio of coal, v	0.339	Langmuir pressure constant, P_L	1.57 MPa
Constant pressure heat capacity of Coal, C_p	1000 J/(kg·K)	Langmuir pressure correction coefficient, c_1	0.07 1/MPa
Gas density at the standard Condition, ρ_{gs}	0.717 kg/m^3	Langmuir volume correction factor, c_2	0.02 1/K
Thermal expansion coefficient of Coal, α_T	2.4×10^{-5} 1/K	Reference temperature for gas adsorption experiment, T_r	300 K

2.4 Model verification

In order to verify the validity of the model, Equation (4) of Sun [11] was compared with Equation (8) of this model to simulate the permeability of coal seams of the two models. Monitoring points A, B and C were selected for comparison, as shown in Figure 3, the curves of the two models basically coincide, so the model is reasonable.

$$\varphi = \alpha + (\varphi_0 - \alpha)\exp\left(-\frac{\Delta\sigma'}{K}\right) \tag{8}$$

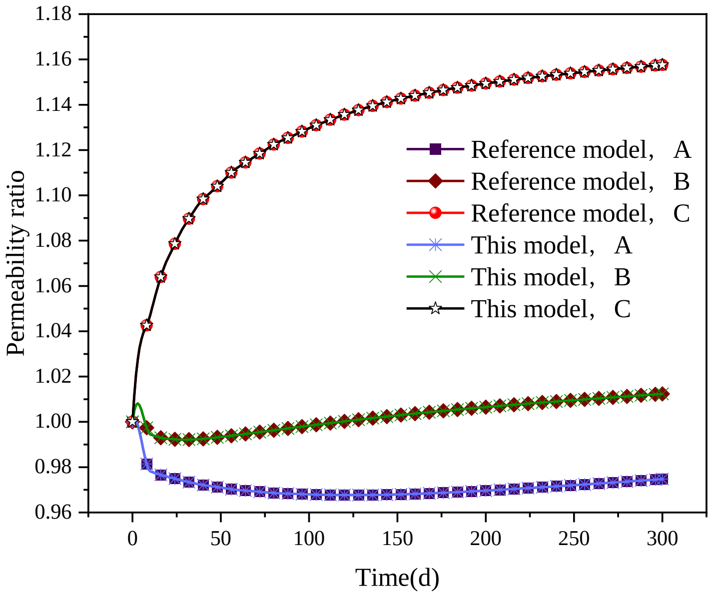


Figure 3: Comparison of permeability changes of different models

3 Results and discussion

3.1 Variation of electric field intensity at different microwave frequencies

As shown in Figure 4, the electric field of coal reservoir attenuates strongly, and it can be considered to have no influence after a short distance. Assuming that the electric field less than 1 V/m is ignored, the range of microwave action can be approximately determined according to the electric field intensity in the direction of EF of the measured line: The microwave penetration zone of 433 MHz and 915 MHz is about 2 m radius with the microwave source as the center of the circle; the microwave penetration zone of 2450 MHz is about 1 m radius with the microwave source as the center of the circle; and the microwave penetration ability of 5800 MHz is poor, and the microwave action range is only about 0.2 m away from the microwave source.

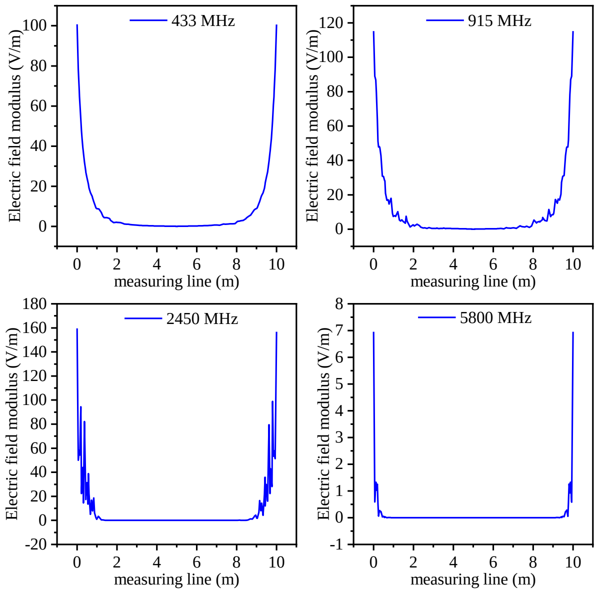


Figure 4: Electric field intensity distribution at EF of measurement line

3.2 Temperature variation of coal seam under different microwave frequencies

Figure 5 and Figure 6 show the temperature distribution cloud map of the coal seam on the 300th day and the changes of the temperature at the monitoring points with different microwave frequencies along with the extraction time. The temperature of coal seam increases gradually with the extension of time, and the temperature near the microwave source is higher, and the farther away from the microwave source, the lower the temperature. This is because after the microwave source is turned on, the electromagnetic field will be formed in an instant, and the coal near the microwave source quickly absorbs microwave energy and is converted into heat energy, while the position far away from the microwave source is less affected by microwave, and this part of the coal seam mainly transfers heat through heat conduction and fluid heat convection. The coal seam at 915 MHz has the most uniform temperature distribution and the overall temperature is higher, followed by 433 MHz, 2450 MHz, and the coal seam at 5800 MHz has the worst thermal effect with almost no change. When the heat injection time reaches 300 days, the lowest temperature of coal seam at 915 MHz microwave frequency is 305.784K and the highest temperature is 381.912K respectively

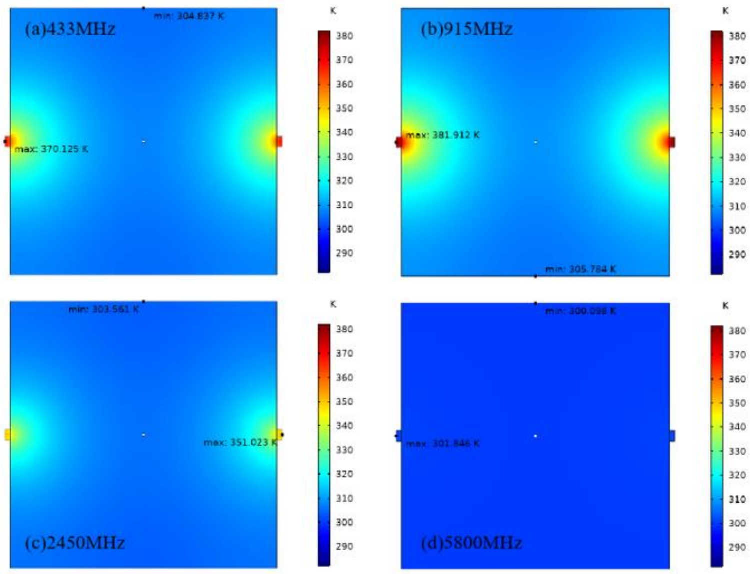


Figure 5: Temperature distribution of coal seam at 300d after heating injection

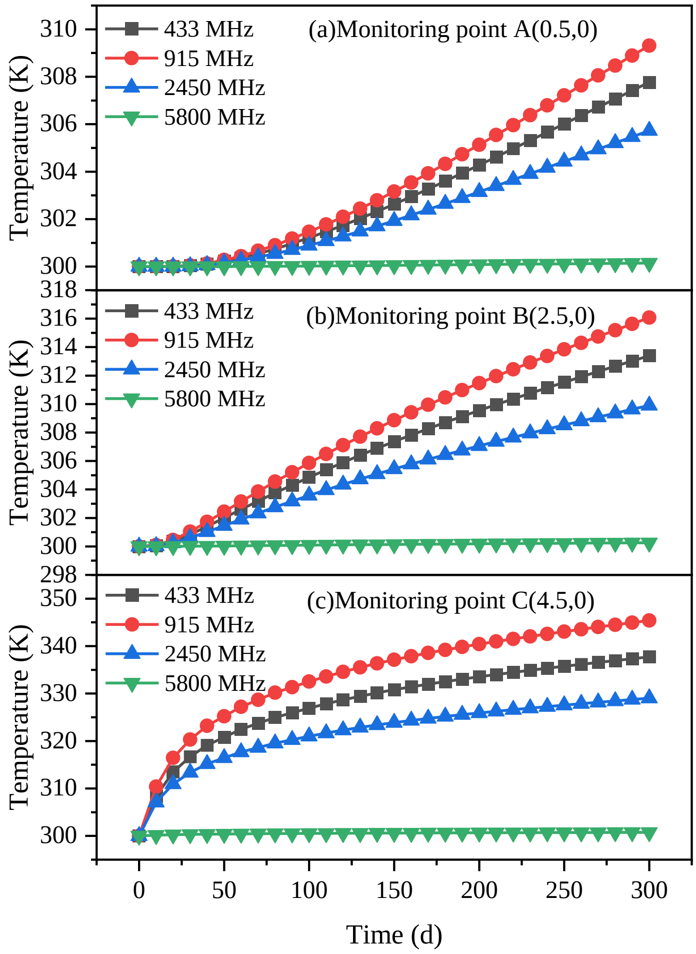


Figure 6: Temperature changes at the monitoring points under different microwave frequencies

3.3 Permeability variation of coal seam at different microwave frequencies

Figure 7 and Figure 8 are three-dimensional views of permeability changes at monitoring points at different microwave frequencies and permeability distribution of coal seam on the 300th day. It can be found that permeability evolution at monitoring points A, B and C presents different rules due to different distances from microwave sources. Among the four frequencies, the permeability curves of 433 MHz, 915 MHz and 2450 MHz are similar, the permeability at point A decreases rapidly after the microwave is turned on, then decreases slowly and then increases gradually, the permeability at point B increases first and then decreases and then increases, and the permeability at point C increases monotonically. Due to its poor thermal effect on coal, 5800 MHz shows different characteristics from the first three, and the permeability of coal seam presents a funnel-shaped distribution. The permeability at point A decreases rapidly and then slowly with the extraction time, and increases and decreases at point B, and decreases monotonically at point C. This is because the coal seam gas pressure near the extraction drilling hole decreases rapidly, the pressure gradient leads to the expansion and deformation of the coal skeleton, and the permeability ratio decreases accordingly. In the early stage of extraction, the vicinity of the drilling hole has not been affected by microwave action, and the permeability ratio under the four frequencies is basically the same at this time, while the temperature near the microwave source rises rapidly, and the thermal effect of the coal body is dominant. The permeability increases rapidly. With the progress of extraction, heat is gradually transferred from the high temperature area of the microwave source to the low temperature area near the borehole, resulting in an increase in the permeability proportion. In general, the permeability of coal seam under 915 MHz microwave is the best.

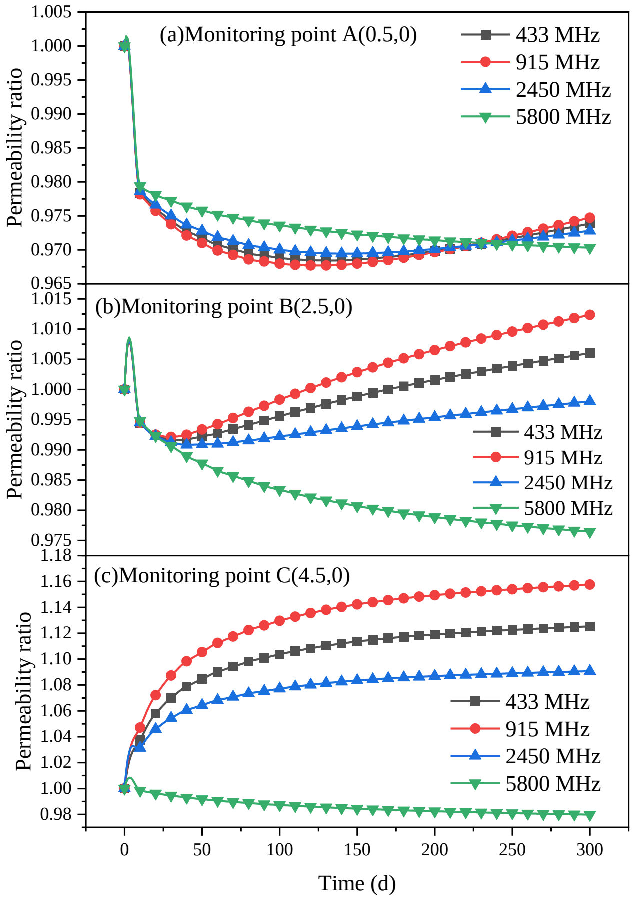


Figure 7: Permeability changes at monitoring points under different frequencies

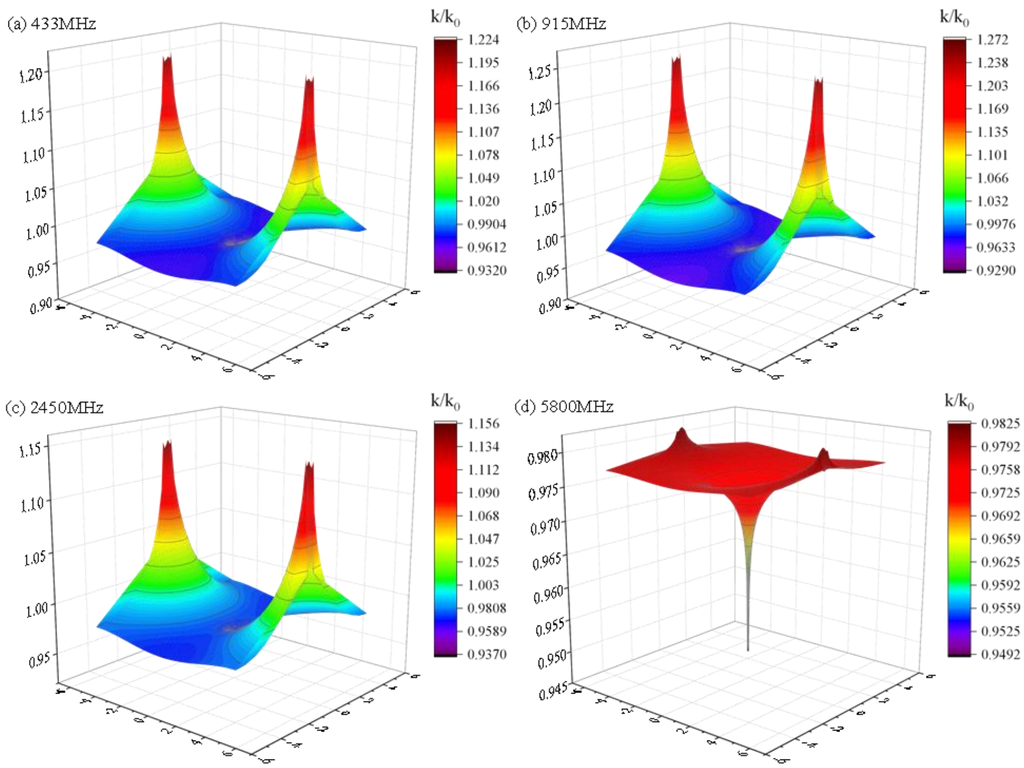
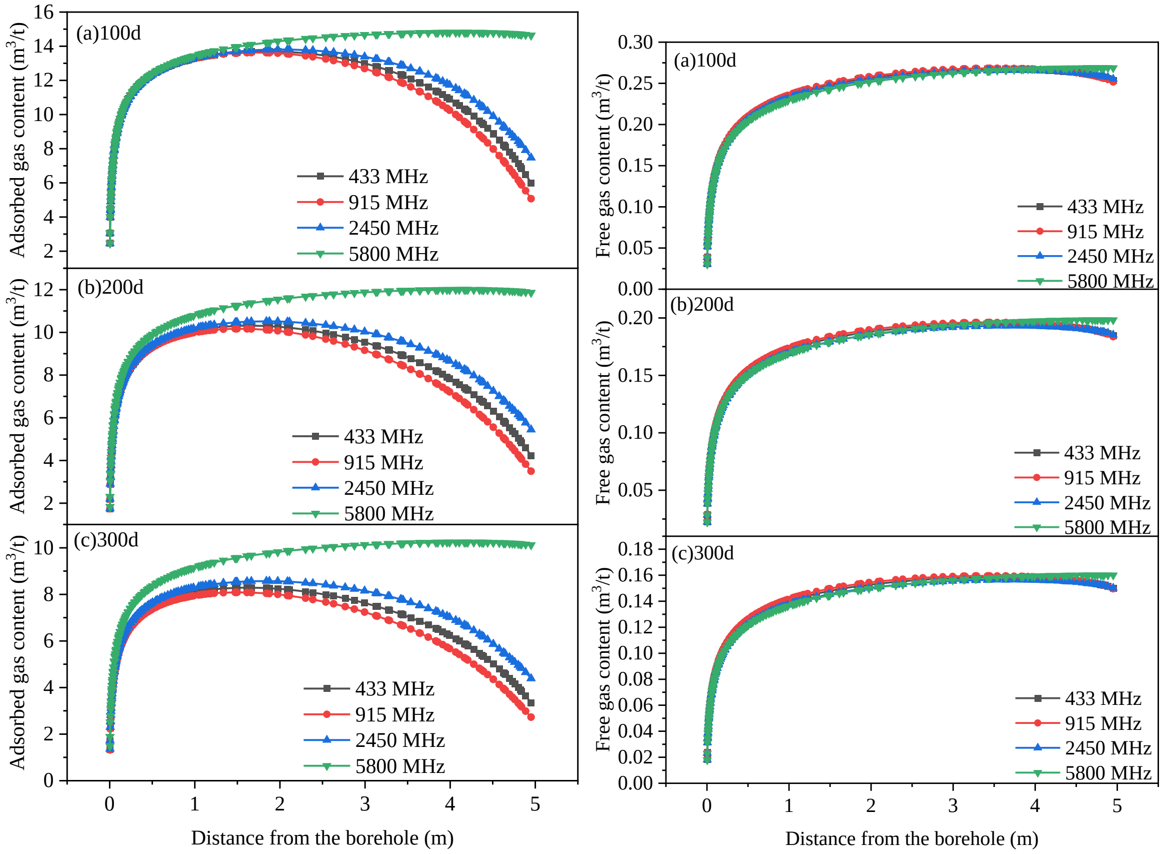


Figure 8: Permeability distribution at the 300d of coal seam under different microwave frequencies

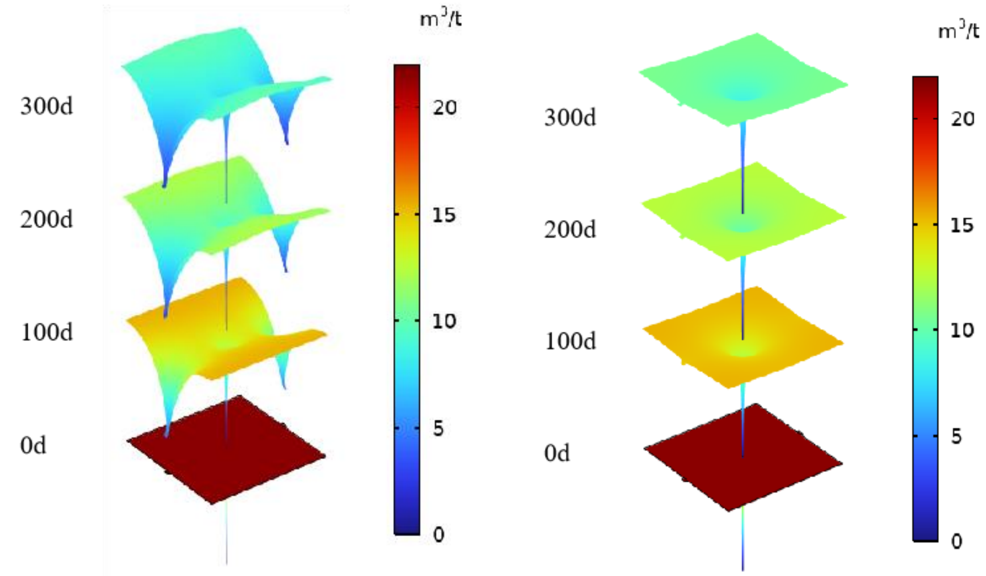
3.4 Variation of coal seam gas content under different microwave frequency

Figure 9 shows the changes of adsorbed gas content and free gas content at different frequencies on the 100th, 200th and 300th day. Most of the gas in coal exists in the form of adsorbed state, while the free gas content is less. Figure 10 shows the evolution cloud diagram of total gas content at 915 MHz and 5800 MHz. The initial gas content of coal seam is 22 m^3/t, and the overall total gas content of coal seam gradually decreases with the progress of extraction. The total gas content of 433 MHz, 915 MHz and 2450 MHz near the borehole and at microwave sources on both sides presents a cliff reduction. The gas content decreases slowly and evenly within 1-3 m distance from the borehole. 5800 MHz coal body has weak thermal effect, and the gas content distribution is more uniform except near the borehole. Under microwave action, coal seam gas gradually desorbed from adsorption state to free state due to thermal effect, and the microwave thermal effect near the microwave source is the most significant, so that a large number of free gas from the microwave source to the extraction borehole migration. On the 300th day of gas extraction, the gas content of 915 MHz coal seam drops to 5-11 m^3/t, and that of 5800 MHz coal seam drops to 10-13 m^3/t.



(a) Adsorbed gas content *(b) Free gas content*

Figure 9: Changes of adsorbed gas content and free gas content at different frequencies



(a) 915 MHz *(b) 5800 MHz*

Figure 10: Cloud map of total gas content evolution at 915 MHz and 5800 MHz

3.5 Coal seam gas extraction at different microwave frequencies

Figure 11 shows the cumulative gas extraction. The cumulative gas extraction of coal seam increases rapidly in the initial stage and then turns to slow growth. At the same time, the cumulative gas extraction of 915 MHz is always the highest and that of 5800 MHz is the lowest. On the 300th day, the cumulative gas extraction of 433 MHz, 915 MHz, 2450 MHz and 5800 MHz increased to 905 m^3, 919 m^3, 885 m^3 and 801 m^3, respectively. Figure 12 shows the gas extraction rate. The gas extraction rate increases rapidly in the initial stage of extraction, then decreases rapidly after reaching the peak and turns to a slow decrease at an inflection point. The peak times of the four microwave frequencies are all on the 6th day, which are 26.36 m^3/d, 26.37 m^3/d, 26.35 m^3/d and 26.18 m^3/d respectively. The gas extraction rates when the extraction time reaches 300 days are 1.25 m^3/d, 1.29 m^3/d, 1.2 m^3/d and 1.11 m^3/d.

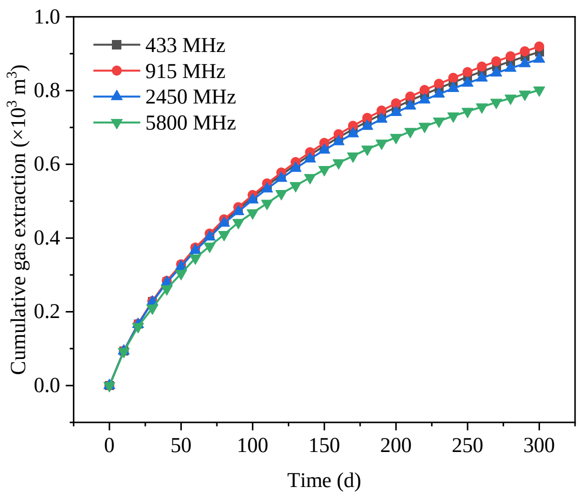


Figure 11: Gas extraction at different frequencies

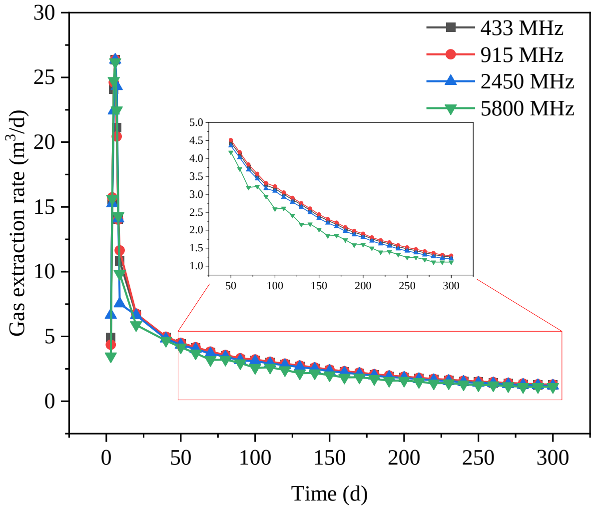


Figure 12: Gas extraction rates of different frequencies

4. Conclusions

(1) The penetration depth is inversely proportional to the microwave frequency, that is, the higher the frequency, the lower the penetration depth. The electric field distribution in coal seam can also indirectly reflect the microwave penetration zone, and the maximum microwave penetration zone of 433 MHz and 915 MHz is about

2 m. The effect range of 5800 MHz microwave is the smallest, only 0.2 m.

(2) After the opening of the microwave source, the nearby coal seam immediately responds, the temperature rises rapidly. With the progress of extraction time, the temperature of the coal seam gradually rises, the heat transfers from the high temperature area to the low temperature area, the temperature difference gradually decreases. 915 MHz microwave has the best heat injection effect on the coal seam, and the permeability of the coal seam increases obviously in the heat-affected area, which can significantly improve the permeability of the coal seam.

(3) Microwave heat injection is beneficial to coal seam gas extraction, the frequency is not larger or smaller, the better, 915 MHz microwave has the best effect on gas extraction, more adsorbed gas into free gas, coal seam gas content decreased the most obvious, the 300th day cumulative gas extraction amount of 919 m^3, the maximum gas extraction rate of 26.37 m^3/d.

Acknowledgments

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