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Numerical simulation of the physical response of shale oil reservoirs under microwave and steam synergy and single heating methods

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This article is the first to simulate the changes in temperature, porosity, permeability, and displacement of oil shale reservoirs under microwave followed by steam and steam followed by microwave and to analyze the oil shale reservoirs under single steam and microwave in comparison, aiming to find out the most suitable way for in-situ exploitation of oil shale among the four types of heating methods. From the results of COMSOL Multiphysics field software, the average temperatures of the reservoir under 600 W single microwave heating, 650 °C single steam heating, steam followed by microwave heating, and microwave followed by steam heating were 570.15, 528.53, 725.66, and 524.36 °C, respectively, at a heating time of 500 days; the average porosity was 16, 18.692, 19.52, and 17.744%, respectively; the average permeability was 4.343×10^{-16} , 2.05×10^{-11} , 1.738×10^{-11} , and 1.09×10^{-11} m², respectively; and the average displacement of the reservoir was 3.3 cm, 3.11 cm, 3.38 cm, and 2.65 cm, respectively. The temperature of the oil shale reservoir increases with time for four heating methods, and the heating distance becomes larger. The reservoir's porosity, affected by steam followed by microwave and single steam, showed a decreasing then increasing trend over 100 days and leveled off after 300 days, while with single microwave and microwave followed by steam, it showed a linear increase. Permeability exhibits minimal variation at reservoir temperatures ranging from 200 to 300 °C but experiences a significant increase above 300 °C. The displacement of the reservoir gradually increases under the four applied methods. The oil shale reservoir treated with steam followed by microwave outperforms the other three methods in heating speed, range, pore connectivity, and oil and gas circulation, offering a new method for future research on oil shale in-situ extraction technologies.

Keywords Oil shale, In-situ extraction, Microwave-steam synergy, Numerical simulation

The focus has shifted with the increasing demand for energy and the depletion of traditional energy resources. The oil depletion in conventional reservoirs has expanded the scope of mining in unconventional reservoirs¹, making unconventional oil and gas resources a significant research focus in many countries. These resources have broad market prospects due to their abundant reserves, wide distribution, and increasingly mature development technologies². Oil shale is a valuable potential source of liquid hydrocarbons and energy for many countries. The oil shale resources in China are about 978 billion tons, of which 632 billion tons are in the Stretch Basin, accounting for 65% of China's total oil shale resources, or about 32 billion tons of in-situ shale oil³. Oil shale, a special type of rock, is rich in organic matter, with mass fractions ranging from 5 to 65 percent, and is an explosive sedimentary rock with a high ash content (mass fraction > 40 percent). Therefore, temperature is a necessary condition for the pyrolysis of oil shale⁴. Temperature changes not only promote the transformation of organic matter but also alter the pore structure of the rock, thereby changing the permeability of the oil shale. Additionally, thermal effects induce thermal stresses within the rock, further affecting its physical properties and permeability, which is crucial for improving oil shale extraction efficiency. Compared to traditional oil

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and gas formations, shale oil and gas formations have poorer mobility and lower permeability⁵, leading to long extraction periods, higher difficulty, and lower efficiency. Selecting an appropriate thermal extraction technique can significantly enhance oil shale recovery efficiency, thereby mitigating the conventional energy scarcity in our nation.

Shale oil extraction can be carried out using two primary methods: above-ground retorting and in-situ extraction⁶. Above-ground retorting technology faces several challenges, including low extraction rates, small operational scales, high extraction costs, and significant environmental pollution. In-situ extraction technology is further categorized based on electrical, convection, and radiative heating methods. Electric heating offers flexible heating modes, simple operation, and easy control. Notable examples include Shell Petroleum Company's ICP technology^{7–9}, Exxon Mobil Corporation's Electrofrac TM technology¹⁰, Independent Energy Partners' GFC technology¹¹, and Jilin University's high-voltage frequency electric heating technology¹². Convection heating, primarily based on steam heating, offers fast heating speeds, short cycles, and high oil yields. Notable examples include Chevron's CRUSH technology¹⁰, Petro Probe's air heating technology¹⁰, EGL's EGL technology¹², and Taiyuan University of Technology's convection heating technology (MIT)¹³. Radiative heating primarily includes microwave heating and radiofrequency heating¹⁴. Microwave heating can penetrate the entire reservoir regardless of its anisotropic characteristics, offering uniform heating, rapid warming, and high energy utilization. Raytheon Company's RF/CF technology¹⁵ exemplifies this method. Radiofrequency heating utilizes high-power radio waves to heat oil shale in three dimensions, enhancing heat transfer within the reservoir. This method is exemplified by Lawrence Livermore National Laboratory's (LLNL) radiofrequency technology¹⁶.

Due to the high cost, extended duration, and complexity of conducting multiple repetitive large-scale tests for in-situ oil shale extraction, numerical simulation offers advantages such as lower cost, high accuracy, and repeatability. It allows for adjusting necessary data and parameters based on site requirements, thereby identifying consistent patterns through simulation.

In recent years, scholars have used numerical simulation software such as Ansys, Fluent, COMSOL and CMG to simulate various research topics related to in-situ oil shale extraction. By summarizing the simulation results of these software, we can better understand their effectiveness and limitations in the in-situ oil shale extraction process. The research is summarized in Table 1 below:

As can be seen from Table 1, the research results that experts and scholars want to obtain by using various numerical simulation software to simulate the in-situ oil shale extraction process can be divided into two categories. The first category involves exploration of extraction methods that can enhance the yield of oil shale, such as well pattern deployment, the introduction of auxiliary extraction fractures, and the addition of auxiliary extraction agents. The second category focuses on investigating the variation patterns of specific parameters during the pyrolysis process of oil shale reservoirs, including temperature, porosity, and permeability, etc. Table 1 shows that for the second category, experts and scholars are accustomed to used COMSOL, a numerical simulation software, for their research. This is because most of the particular parameters of a variety of coupling between the relationship between the COMSOL numerical simulation software in the multi-field coupling has a significant advantage, which is for this paper to choose the numerical simulation software to study the specific parameters of the oil shale under the synergistic action of the microwave and the steam. Meanwhile, researchers and scholars in recent years have provided a good data model for this paper to study the changing law of specific parameters of oil shale under the synergistic effect of microwave and steam. However, the experts and scholars in the table only simulated a single thermal mining mode, whether by electric heating, hot nitrogen heating, steam heating, near-critical water heating, or microwave heating, and this paper is the first time to consider the use of water vapour with a high relative dielectric constant, combined with the conditions in the microwave can play a rapid heating effect, to consider the two modes of the synergistic effect of the thermal mining mode. So, in this paper, a multi-field coupling model will be developed using COMSOL software. The model will transition from a single microwave and high-temperature steam heating to a combined microwave-steam heating model. The study will analyze the distribution pattern of the temperature, permeability, and displacement fields in the oil shale reservoir and make a comparative analysis of temperature, porosity, permeability, and displacement, aiming to find a more efficient extraction plan and improve the efficiency of oil and gas extraction.

Heating methods

Microwave heating technology

Microwave heating and radiofrequency heating are the primary types of radiative heating. Microwaves are a type of electromagnetic radiation with a wavelength range of 0.001–1 m and a frequency between 300 and 0.3 GHz²⁷. The core advantage of microwave heating is its ability to penetrate the entire reservoir regardless of its shape and heterogeneity. It can heat the oil shale reservoir to the required temperature for hydrocarbon production, offering flexible heating, uniform heating, and high energy utilization, making it suitable for high-power pyrolysis conditions²⁸. Based on the mechanism of microwave interaction with materials, they are classified into three types: microwave insulating medium, microwave penetration medium, and microwave absorbing medium. A microwave insulating medium completely reflects microwaves and does not absorb them. A microwave penetration medium allows microwaves to pass through entirely. A microwave-absorbing medium absorbs microwaves as they pass through, as shown in Fig. 1.

Since oil shale is a weak microwave-absorbing medium, and water has a high dielectric constant, particles with a high dielectric constant can be added to the microwave to improve heating efficiency. This provides strong theoretical support for the microwave-steam co-heating mode for oil shale extraction.

The conversion of electromagnetic energy into thermal energy of a substance in a microwave electromagnetic field can be expressed by the following equation²⁹:

$$W = 2\pi f \varepsilon_0 \varepsilon'_r E^2 V \tan \delta \tag{1}$$

References	Software	Research content	Conclusion	
Sun et al. ¹⁷	Ansys	Numerical simulation and optimization study of In-Situ Heating for three-dimensional oil shale exploitation with different well patterns	In the whole in-situ heating process of oil shale, the well network model consisting of eight heating wells and one production well with adjacent heating wells connected to the production well at an angle of 45° has the lowest power consumption per unit volume of 814.8 kWh. The power consumption was the lowest at 814.87 kW/m ³ and the energy utilization efficiency was the highest. This is a significant reduction of 41.93% in power consumption per unit volume compared to the other six well network models. This is a significant 41.93% reduction in power consumption per unit volume compared to the other six well network models.	
Jia et al. ¹⁸	COMSOL	Thermo-hydro-mechanical coupling in oil shale: Investigating permeability and heat transfer under high- temperature steam injection	The study integrates theoretical analysis and numerical simulations to uncover the fundamental connections between internal permeability and heat transfer mechanisms during steam injection. It reveals that oil shale undergoes two critical evolutionary phases: a stability phase below 350 °C, where volatile dispersion occurs, and a rapid increase phase above 350 °C, marked by significant microstructural changes from micro-fractures to extensive through-going fractures due to intense thermal decomposition. This decomposition leads to increased gas production and enhanced thermal fracturing. The threshold temperature is identified at 400 °C, above which the oil shale's mechanical strength and pore pressure increase, leading to decreased volumetric compression until stabilization	
Sun et al. ¹⁹	Fluent	Numerical study on enhanced heat transfer of downhole slotted-type heaters for in situ oil shale exploitation	Numerical studies are conducted on the heat transfer performance and shell-side fluid flow characteristics of a perforated plate-type heater. The variations of the heat transfer factor N_u , friction factor f , and evaluation parameter $N_u/f^{t/3}$ are analyzed for different helix angles β and ratios of the long and short semiaxes of the circular holes on the heating plate under different Reynolds numbers R_e . The results reveal that under the same shell-side Reynolds number R_e , the heat transfer factor N_u shows an increasing trend with the increase in the proportion of the helix angle β	
Chen et al. ²⁰	CMG	An effective numerical simulation method for steam injection assisted in situ recovery of oil shale	An effective numerical simulation method is proposed for production prediction of in-situ recovery from steam- injected oil shale reservoirs. In this method, a finite volume based discretization scheme for the heat and mass transfer equations of the thermal constitutive model is derived and used. An embedded discrete fracture model is used to accurately treat fractured vertical wells. A smooth nonlinear solver is proposed to solve the global equations, and then cell pressure, temperature, saturation, component mole fraction and well productivity can be obtained	
Yang et al. ²¹	CMG	Numerical simulation of the development effect of oil shale autogenous thermal in-situ conversion in straight and horizontal wells	Taking oil shale in Xunyi area of Ordos Basin as the research object, numerical simulation method was used to compare the development effect of oil shale autogenous thermal in-situ transformation between straight wells and horizontal wells, and the difference in the development effect of oil shale autogenous thermal in-situ transformation between straight wells and horizontal wells was investigated	
Zhang et al. ²²	COMSOL	Simulation of in-situ steam-driven oil seepage in single-fracture oil shale CT digital cores after pyrolysis at different temperatures	Based on the digital cores of oil shale obtained from high-temperature steam in-situ pyrolysis and micro-CT scanning experiments, the real structure of oil shale after pyrolysis at different temperatures is seamlessly integrated into COMSOL through precise grid division, and it is concluded that the degree of development of the pore structure and the connectivity has a significant impact on the advancement speed of the phase interface—the better the degree of development of the pore structure, the faster the advancement speed of the phase interface	
He ²³	Fluent	Near-critical water in-situ oil shale extraction	The heating effect of unidirectional heat injection could be better. The simulation results of temperature field, asphalt extraction rate, and porosity show that the oil shale layer can be heated to the desired temperature faster by intermittently switching heat injection wells and production wells. The desired heating effect and asphalt extraction rate can be obtained after 80 days of heating by changing the heat injection wells and the production wells and the production wells once every 30 days	
Zhu ²⁴	COMSOL	Three-dimensional numerical simulation on the thermal response of oil shale subjected to microwave heating	The influence of microwave frequency and power on the temperature distribution of oil shale sample is investigated. The results reveal that the temperature distribution of oil shale sample is not uniform under microwave heating due to the nonuniform distribution of electric field. Microwave heating is most efficient at a frequency of 2.45 GHz because of the size and shape of rectangular waveguide. The temperature rise of oil shale is characterized by "slow-fast", because the dielectric property of oil shale is temperature-dependent	
Wang ²⁵	COMSOL	Anisotropic evolution of thermophysical, seepage, and mechanical characteristics of oil shale under high temperatures	The temperature field distribution of the oil shale reservoir is closely related to the transportation of superheated vapor in the reservoir, and a zone of rapid temperature decrease is formed at the edge of the temperature field; the factor that has the greatest influence on the oil and gas production is the anisotropy of the seepage rate, followed by the anisotropy of the mechanical parameter. The anisotropy of each of the heat transfer coefficients does not have much influence on the oil and gas production	
Zhao ²⁶	COMSOL	Study on the mechanical properties of oil shale pyrolysis and percolation law under the action of microwave	The size of microwave power affects the heating rate, the change of reservoir temperature field is closely related to the microwave pyrolysis time, the permeability inside the reservoir increases with the increase of microwave pyrolysis time, and the rise of reservoir porosity promotes the oil and gas seepage. The reservoir will produce larger displacement under high power. Comprehensively, 600 W is the most suitable power under three kinds of power	

Table 1. Results obtained by experts and scholars using different software to study various problems.

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$$p'' = 2\pi f \varepsilon_0 \varepsilon'_r E^2 \tan \delta \tag{2}$$

where W is the absorbed microwave power, W; p'' is the volumetric energy density; f is the frequency of the microwave, HZ; ε_0 is the vacuum dielectric constant; ε'_r is the dielectric constant of the medium; $\tan \delta$ is the tangent of the dielectric loss angle; δ is the dielectric loss angle; E is the effective electric field strength inside the substance, V/m; and V is the effective volume of the absorbed microwave.

The amount of dielectric loss is related to the dielectric constant of the medium. In a lossy medium, the dielectric constant has a complex form³⁰:

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 \left(\varepsilon' - j \varepsilon'' \right) \tag{3}$$

The complex relative permittivity is expressed in the form:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{4}$$

where ε_0 is the vacuum permittivity, $\varepsilon_0 = 8.8542 \times 10^{-12}$ F/m; ε_r is the relative permittivity of the medium; ε' is the real part of the permittivity, the usual sense of the medium's permittivity; j is the imaginary unit; ε'' is the imaginary part of the permittivity, which is the loss factor.

The loss profile of a medium can be expressed as the tangent of the loss angle of the medium:



Fig. 1. Different media materials.



Fig. 2. Steam flows through pores to heat oil shale reservoirs.

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon''_r}{\varepsilon'_r} \tag{5}$$

Steam heating technology

High-temperature steam in-situ extraction of oil shale involves continuously injecting high-temperature steam into the reservoir through injection wells. The injected fluid transfers heat to the oil shale via the pores, as shown in Fig. 2, causing the organic matter in the oil shale to pyrolyze through convective heat transfer. This process drives the oil and gas towards the production wells, where they are separated into oil, gas, and water. Compared to conduction heating, steam convection heating more effectively increases the number of pores in oil shale, expands pore diameters, increases pore mass, improves pore connectivity, and enhances the permeability of oil shale. This production of oil and gas resources³¹. The disadvantage is that the free flow of steam during the heating process results in significant heat energy loss. Additionally, high-temperature steam pressure can cause like ground subsidence and groundwater contamination.

Numerical simulation of oil shale pyrolysis Geometric model

The simulated oil shale reservoir has dimensions of 16 m in length, 12 m in width, and 10 m in height, with 10 m of rock above and below the reservoir. A hydraulic fracture with a width of 0.1 m and a length of 12 m was created inside the reservoir to increase hydrocarbon permeability. An extraction well connected to the surface was drilled in the middle, and injection wells were evenly distributed to the left and right of the fissure for



Fig. 3. Conceptual diagram of a geometric model of a pyrolytic oil shale reservoir.



Fig. 4. Probe location diagram.

placing microwave emission ports and injecting high-temperature steam, as shown in Fig. 3. Four probes were placed between the injection and extraction wells to observe changes in temperature, porosity, permeability, and displacement at different locations. A coordinate system was established with the bottom-left point as the origin (0,0), placing probes at four locations with positional coordinates: Probe A (4.5, 8.6), Probe B (5.5, 7.8), Probe C (6.5, 7.1), and Probe D (7.5, 6.3), as shown in Fig. 4. The grid was divided into fine cells, as shown in Fig. 5.

Electromagnetic-thermal-fluid-solid multi-field coupled control equations.

Control equations of electromagnetic field

Microwaves are a type of electromagnetic wave and the electromagnetic field in oil shale can be represented by a system of Maxwell's equations^{32,33}:

$$\nabla \cdot \vec{D} = \rho_{\rm e} \tag{6}$$

$$\nabla \cdot \vec{B} = 0 \tag{7}$$

$$\nabla \times \overrightarrow{H} = \overrightarrow{J} + \frac{\partial \overrightarrow{D}}{\partial \overrightarrow{t}}$$
(8)

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial \vec{t}}$$
(9)



Fig. 5. Grid division diagram.

where \vec{E} is the electric field strength, V/m; \vec{D} is the electric flux density, C/m²; \vec{H} is the magnetic field strength, A/m; \vec{B} is the magnetic flux density, Wb/m³; \vec{J} is the current density, A/m²; $\rho_{\rm e}$ is the charge density, C/m³; Introducing the intrinsic equations of the medium:

$$\overrightarrow{D} = \varepsilon_0 \varepsilon_r \overrightarrow{E} \tag{10}$$

$$\vec{B} = \mu_0 \mu_r \vec{H} \tag{11}$$

$$\vec{J} = \sigma_e \vec{E} \tag{12}$$

where ε_0 is the vacuum permittivity, $\varepsilon_0 = 8.8542 \times 10^{-12}$ F/m; ε_r is the relative permittivity of the medium; μ_0 is the free-space magnetic permeability, whose value is taken as $4\pi \times 10^{-7}$, H/m; μ_r is the relative magnetic permeability; and σ_e is the electrical conductivity, S/m.

The Helmholtz vector equations for the time-varying electromagnetic field are obtained by bringing the intrinsic equations of the medium into Maxwell's system of equations³⁴:

$$\nabla \times \mu_{\rm r}^{-1} \left(\nabla \times \vec{E} \right) - k_{\rm c}^2 \left(\varepsilon_{\rm r} - \frac{j\sigma_{\rm e}}{\omega\varepsilon_0} \right) \vec{E} = 0$$
⁽¹³⁾

where k_c is the free space wave number, F/m; ω is the angular frequency, rad/s; and j is the imaginary unit. Where k_c can also be expressed as:

$$k_{\rm c} = \omega \sqrt{\mu_0 \varepsilon_0} \tag{14}$$

The relative dielectric constant determines the microwave heating efficiency of a material, and the relative dielectric constant can be written as:

$$\varepsilon_{\rm r} = \varepsilon' - j\varepsilon'' \tag{15}$$

where ε' is the dielectric constant of the material and ε'' is the corresponding loss coefficient of the material.

Control equations of temperature field Heat transfer equation³⁴ with convective term:

 $\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q$

e density of oil shale, kg/m³;
$$C_p$$
 is the specific heat capacity of the oil shale reservoir, J/kg · K; T

where ρ is the density of oil shale, kg/m³; C_p is the specific heat capacity of the oil shale reservoir, J/kg · K; *T* is the temperature; *u* is the velocity of the fluid inside the material, m/s; *q* is the heat flux, W/m²; *Q* is the heat source W/m³.

In case of steam heating or microwave heating, the heat flux q can be written as³⁴:

$$q = -k_y \nabla T \tag{17}$$

where k_y is the equivalent thermal conductivity of the porous medium³⁴, W (m K), which is given by:

$$k_y = \theta_p k_s + (1 - \theta_p) k_f \tag{18}$$

(16)

where k_s is the thermal conductivity of the oil shale, W (*m K*); k_f is the thermal conductivity of the fluid within the porous medium, W (*m K*); θ_p is the solid volume fraction, this value varies with the decomposition of kerogen.

When the microwave heating process was carried out, the kerogen inside the oil shale was not pyrolyzed into oil gas and, therefore, u was 0 m/s, and the modified heat transfer equation was obtained:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k_y \nabla T) = Q \tag{19}$$

When microwave preheating of oil shale is performed, part of the electromagnetic energy is converted into heat energy equation is (combined with the Poynting vector equation³³):

$$Q_e = Q_{rh} + Q_{ml} \tag{20}$$

$$Q_{rh} = \frac{1}{2} \operatorname{Re} \left(J \cdot E^* \right) \tag{21}$$

$$Q_{ml} = \frac{1}{2} \operatorname{Re} \left(i\omega B \cdot H^* \right) \tag{22}$$

where Q_e is the electromagnetic loss power, W/m³; Q_{rh} is the resistive loss, W/m³; Q_{ml} is the magnetic loss, W/m³; E^* is the conjugate of E; H^* is the conjugate of H; and Re denotes the taking of the real part.

In microwave radiation technology, the role of the electromagnetic loss of power can be viewed as a heated heat source brought into the heat transfer equation to get the temperature field equations containing the effect of microwave radiation, namely, the electromagnetic-thermal coupling equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k_y \nabla T) + \frac{1}{2} \left[\operatorname{Re} \left(J \cdot E^* \right) + \operatorname{Re} \left(i \omega B \cdot H^* \right) \right]$$
(23)

In high-temperature steam heating, the action temperature is used as the heat source phase Q.

Control equations of deformation field

The general solid deformation control equation consists of three equations: the stress balance equation, the geometric deformation equation, and the constitutive equation, generally in the form of Navier³⁵:

$$\begin{cases} \frac{E}{2\left(1+\mu\right)\left(1-2\mu\right)}\frac{\partial\varepsilon_{v}}{\partial x} + G\nabla^{2}u + F_{x} = 0\\ \frac{E}{2\left(1+\mu\right)\left(1-2\mu\right)}\frac{\partial\varepsilon_{v}}{\partial y} + G\nabla^{2}u + F_{y} = 0\\ \frac{E}{2\left(1+\mu\right)\left(1-2\mu\right)}\frac{\partial\varepsilon_{v}}{\partial z} + G\nabla^{2}u + F_{z} = 0 \end{cases}$$
(24)

where *E* is the modulus of elasticity, MPa; *G* is the shear modulus of elasticity, MPa, $G = E/2(1 + \mu)$; μ is the Poisson's ratio of oil shale;

into the tensor form:

$$\frac{G}{(1-2\mu)}u_{j,ji} + Gu_{i,jj} + F_i = 0$$
(25)

Considering the effect of pore pressure and thermal expansion stresses, the stress balance equation expressed in terms of displacement is:

$$\frac{G}{(1-2\mu)}u_{j,ji} + Gu_{i,jj} + \alpha p_i + F_i + K\omega T_i = 0$$
⁽²⁶⁾

where *G* is the shear modulus of elasticity, MPa; $G = E/2(1 + \mu)$; μ is the Poisson's ratio of oil shale; u_i is the rock displacement vector, m; α is the Biot coefficient; p_i is the pore pressure, MPa; F_i is the body force component, KN; and ω is the thermal stress coefficient, $\omega = KE/(1 - 2\mu)$, where *K* is the anisotropic coefficient of thermal expansion of oil shale.

Control equations of seepage field Equation of state for rocks³⁶:

$$C_f = \frac{dV_p}{V_f} \cdot \frac{1}{dp}$$
(27)

where C_f is the compression coefficient of the rock; V_p is the pore volume; V_f is the volume of the rock. dV_p/V_f can be expressed in terms of changes in porosity³⁶:

$$d\varphi = \frac{dV_p}{V_f} \tag{28}$$

Combining Eqs. (27) and (28) yields:

$$C_f = \frac{d\varphi}{dp} \tag{29}$$

Separate variables on both sides are integrated to obtain:

$$\varphi = \varphi_0 + C_f \left(p - p_0 \right) \tag{30}$$

Disregarding the presence of sources and sinks, the total change in fluid mass within the cell at dt time and the change in mass within the cell at dt time satisfy conservation of mass³⁷:

$$\frac{\partial \left(\rho\varphi\right)}{\partial t}dV \cdot dt = -\nabla \cdot \left(\rho u\right)dV \cdot dt \tag{31}$$

The seepage equation for Darcy's law³⁸, applicable to the low-velocity motion of oil and gas in oil shale, is obtained without considering the effect of gravity:

$$\frac{\partial \left(\rho\varphi\right)}{\partial t} + \nabla \cdot \left(-\rho \frac{k}{\mu} \nabla p\right) = 0 \tag{32}$$

Boundary condition configuration

Electromagnetic fields

The initial conditions are set with an electric field strength (E=0). The surrounding is configured to the scattering boundary condition, with the oil shale injection well designated as the incidence port. The microwave inlet pressure is set to 3 MPa, and the outlet well pressure is set to an atmospheric pressure of 0.1 MPa. The microwave frequency is set to 2.45 GHz, with power levels set at 400, 600, and 800 W.

Temperature field

The initial condition under microwave heating is set to $T_0 = 20$ °C. The porous medium model in solid heat transfer is configured with free boundary conditions around it. For steam heating injection, the heat loss of steam in the subsurface is not considered. The injected steam temperature is set to $T_0 = 650$ °C, with the edge of the wellhead configured as a heat source to maintain continuous injection of high-temperature steam.

Deformation field

The initial displacement and velocity conditions are set to 0. The top is subjected to a uniform load of $\sigma z = 0.4$ MPa in the vertical direction. The perimeter is roll-supported, meaning no displacement occurs along the perimeter.

Seepage field

The initial conditions set the initial pressure of the rock formation at 3 MPa. The oil and gas extraction wells have a fixed pressure of 0.1 MPa. The microwave injection wellhead pressure is set at 3 MPa, and the steam injection wellhead pressure is also set at 3 MPa, with an impermeable boundary set around.

Physical properties of oil shale

Water vapor and water density, kinetic viscosity, specific heat, heat transfer, porosity, and temperature as a function of temperature were solved according to Kang³⁹ using the Galerkin finite element method:

$$\begin{cases} \rho_g = 2272.7 \frac{p \times 10^{-6}}{T + 237.15} \\ \rho_w = (0.9967 - 4.615 \times 10^{-5}T - 3.063 \times 10^{-6}T^2) \times 10^3 \end{cases}$$
(33)

$$\begin{cases} \mu_g = (0.36T + 88.37) \times 10^{-7} \\ \mu_w = \left(\frac{1.743 - 1.8T}{47.7T + 759}\right) \times 10^{-3} \text{ (Pa s)} \end{cases}$$
(34)

$$\begin{cases} C_g = -0.0001T^3 + 0.0948T^2 - 27.103T + 9246.8\\ C_w = 0.0165T^2 - 1.4878T + 4207.4 \end{cases} (J/(kg K))$$
(35)

$$\begin{cases} \lambda_g = 1.0 \times 10^{-8} T^3 - 4.0 \times 10^{-6} T^2 + 0.0006T + 0.0078 \\ \lambda_w = -1.26 \times 10^{-5} T^2 + 2.56 \times 10^{-3} T + 0.5513 \end{cases} (W/(m \text{ K}))$$
(36)

$$\lambda_s = 2.4 - 0.39 \left[\exp\left(\frac{T - 553.3}{T + 130}\right) - 1 \right] (W/(m \text{ K}))$$
(37)

$$\varphi_s = -5.0 \times 10^{-7} T^3 + 0.0005 T^2 - 0.1028 T + 7.261$$
(38)

The relationship between temperature and thermal conductivity was obtained through pyrolysis experiments of oil shale at powers of 400, 600, and 800 W. The relationship between elastic modulus and temperature of oil shale was obtained through uniaxial compression tests before and after pyrolysis. Finally, the porosity variation with temperature was obtained by scanning the oil shale specimens before and after microwave pyrolysis with X-ray CT. The thermal conductivity, porosity, and elastic modulus at different powers were fitted with temperature to obtain relevant functions (see co-author Zhao²⁶ for details):

$$\begin{cases} \lambda_{400W} = -4.695 \times 10^{-4}T + 1.896 \\ \lambda_{600W} = -5.47 \times 10^{-4}T + 1.891 \quad (W/(m \text{ K})) \\ \lambda_{800W} = -6.688 \times 10^{-4}T + 1.889 \end{cases}$$
(39)

$$\begin{cases} \varphi_{400W} = 9.337 \times 10^{-5}T - 5.693 \times 10^{-3} \\ \varphi_{600W} = 1.872 \times 10^{-4}T - 6.674 \times 10^{-3} \\ \varphi_{600W} = 2.309 \times 10^{-4}T - 8.005 \times 10^{-3} \end{cases}$$
(40)

$$\begin{cases} E_{400W} = 2.933 - 0.00278T \\ E_{600W} = 2.997 - 0.00303T \text{ (GPa)} \\ E_{800W} = 2.952 - 0.00279T \end{cases}$$
(41)

Table 2 summarizes the other physical parameters.

4

Result and discussion

Numerical simulation results of single microwave heating

Single microwave heating-temperature field

The microwave pyrolysis process of oil shale is primarily divided into two stages: the thermal pyrolysis of organic matter into bitumen and the subsequent thermal decomposition of bitumen into oil, gas products, and semicoke as the temperature increases. Numerous domestic studies have shown that kerogen begins to pyrolyze into a small portion of shale oil at 350 °C, with most converting into bitumen. At 500 °C, bitumen pyrolyzes into shale oil and semi-coke, and at 600 °C, the oil shale undergoes complete pyrolysis. Figures 6, 7, and 8 illustrate the variation in the temperature field at 2.45 GHz with microwave powers of 400, 600, and 800 W. The figures clearly show that temperature increases over time. The oil shale reservoir near the injection wellhead warms up rapidly, and the area around the microwave emission port shows higher temperatures first, within one day of heating. Over time, the temperature of the oil shale reservoir continues to increase. At a microwave power of 400 W and a heating duration of 500 days, the temperature at the microwave launching port peaks at around 550 °C. However, at microwave powers of 600 and 800 W, the temperature at the launching wellhead reaches 750 °C, which exceeds the temperature required for the final dissolution of oil shale. Such high temperatures may cause the oil shale skeleton to continue heating, leading to destabilization. Additionally, excessive temperatures can induce secondary reactions in the oil and gas, affecting extraction efficiency.

From Fig. 9, it can be observed that under the high power of 600 and 800 W, the average temperature of the oil shale reservoir can reach 550 °C, which is close to the final dissolution temperature of oil shale. However, under the low power of 400 W, the average temperature of the temperature field only reaches 400 °C. There is a sudden rise in temperature during the initial stage of microwave heating (0–50 days) due to the reservoir containing

Physical quantity	Symbol	Oil shale parameters	Unit
Fluid thermal conductivity	k _f	0.026	W(m K)
Shale oil density	ρ_s	2130	kg/m ³
Relative permittivity	ε'	1.68	
Electrical conductivity	ε"	0.02	S/m
Initial porosity	ε_p	5.4	%
Oil shale constant pressure heat capacity	C _p	1980	J/(kg K)
Poisson's ratio	μ	0.4	
Initial permeability	k ₀	2.67×10^{-17}	m ²
Dynamic viscosity of oil-gas mixture	μ_f	1.8e ⁻⁵	Pa s
Oil shale fluid density	ρ_f	600	kg/m ³
Relative magnetic permeability	μ_r	0.03	
Constant pressure heat capacity of oil shale fluids	$C_{p,f}$	2062	J/(kg K)
Relative magnetic permeability	μ_r	0.03	
Oil shale matrix density	ρ_b	1250	kg/m ³

Table 2. Physical properties of oil shale.

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Fig. 7. Temperature variation of oil shale reservoir under 600 W power.



Fig. 8. Temperature variation of oil shale reservoir under 800 W power.





about 3% water. The presence of approximately 3% water in the reservoir, which has a high dielectric constant, rapidly absorbs microwave energy, heating the reservoir. As the temperature continues to rise, the water content decreases, leading to water evaporation and a reduced rate of temperature increase, resulting in a more stable temperature rise. Under 400, 600, and 800 W, the maximum temperature difference increases with time. The higher the power, the greater the temperature difference, indicating more uneven heating of the reservoir. At 400 W, the maximum temperature difference tends to flatten out after 50 days, whereas at 600 and 800 W, the maximum temperature difference continues to rise, due to the ongoing pyrolysis of the oil shale. This is due to the pyrolysis temperature of the oil shale itself. At 350 °C, oil shale pyrolyzes into bitumen and a small amount of oil and gas. At 500 °C, bitumen undergoes secondary pyrolysis into oil, gas, and semi-coke. At 400 W, the average temperature can only reach 400 °C, insufficient for further pyrolysis, causing the temperature difference

to flatten out. However, at 600 and 800 W, the average temperature exceeds 500 °C, leading to a continued rise in connectivity pore temperature and thus an increasing temperature difference.

Based on the temperature field results of oil shale heated by microwaves at different power levels, the optimal power for microwave heating of the oil shale reservoir is determined to be 600 W. Next, only the change rules of porosity, permeability, and displacement of the oil shale reservoir under 600 W will be analyzed.

Single microwave heating-porosity and permeability

During the microwave heating process, the oil shale reservoir absorbs the energy generated by microwave heating. At 0-350 °C, the water in the reservoir evaporates, and some adsorbed oil and gas are released through thermal desorption, freeing the space originally occupied by the water and adsorbed gases. The organic matter in the reservoir softens due to the heat, causing slight thermal expansion, which compresses and deforms the pore space, affecting the pore structure in the reservoir. Simultaneously, the inorganic materials in the reservoir undergo thermal expansion, causing thermal fractures at the contact surfaces and forming small cracks. Between 350 and 500 °C, the oil shale in the reservoir undergoes vigorous reactions, with different chemical structures experiencing thermal fractures in a short time. The organic matter undergoes pyrolysis, forming new pores in the spaces previously occupied by the organic matter, leading to a sudden increase in pore numbers and the formation of pore networks. Between 500 and 600 °C, the pyrolysis reaction of oil shale nears completion. Due to high temperatures, inorganic material in the reservoir forms carbon coke, causing matrix particles to loosen and disintegrate, leading to pore wall collapse and blockage of some pore spaces.

Figures 10 and 11 show the porosity and permeability distribution of the oil shale reservoir at 600 W. It can be seen that the porosity and permeability near the microwave incidence port are larger than those farther away. Over time, the porosity and permeability of the reservoir increase, with smaller values the farther one is from the microwave incidence port.

Figure 12 shows that the porosity and permeability of the oil shale grow rapidly at point A, near the wellhead. The growth of porosity at the four points is linear, and the permeability at these points grows slowly from 1 to 200 days during the pre-injection period. After 200 days, the permeability starts to increase significantly. Oil shale porosity change and permeability change show completely different variability. The porosity increases rapidly and then gradually becomes slower, while the permeability increases slowly and then rapidly. The main reason for the difference is the pyrolysis temperature of the kerogen in the oil shale. For the first 200 days of microwave pyrolysis, the porosity of oil shale grows rapidly and the permeability change is relatively small, this is because in the pre-heating period, the temperature of oil shale reservoir is less than 300 °C, the thermal stress increases with the increase of temperature, when the thermal stress is greater than the strength limit between the two kinds of mineral particles in the oil shale, small thermal rupture occurs, and meanwhile, in the reservoir temperature is less than 300 °C, a small amount of kerogen in the pore space will be pyrolyzed, forming pore space but not able to form a connected area, and most of the kerogen in the reservoir has no way to be



Fig. 10. Porosity variation at 600 W.



Fig. 11. Permeability variation at 600 W.





pyrolyzed, resulting in the permeability inside the reservoir can not be increased, and after heating for 300 days, the temperature of the reservoir will rise to 300 °C, and the kerogen inside will accelerate pyrolysis into oil and gas, and a more complete seepage channel will gradually be formed inside the oil shale reservoir, so that the magnitude of the change in the permeability will be increased.

Single microwave heating-displacement field

The increase in temperature is accompanied by changes in the elastic modulus of the oil shale reservoir, leading to changes in ground stress and causing reservoir displacement. From the displacement diagram in Fig. 13. At 600 W, it can be seen that over time, the displacement at the artificial crack increases. The reservoir moves as a whole towards the crack, and at 500 days, the maximum displacement of the reservoir is 7.47 cm, with an average

displacement of 3.3 cm. In the early stage of microwave heating, the oil shale near the wellhead is weakened by the influence of temperature, leading to thermal expansion, and the displacement gradient appears curved. As the temperature increases, the displacement gradient shows the overall movement of the reservoir, with larger displacements at the extraction wellhead and artificial fracture.

For each monitoring point outside the microwave-transmitting wells, the heating of the microwavetransmitting wells significantly differed in the displacements at various locations within the oil shale reservoirs, and the resulting displacement changes were also relatively large. From the displacement trends at different locations shown in Fig. 14, it can be seen that the displacements of the four probes A, B, C, and D vary linearly. From the displacement change of each observation point, it can be observed that as the time of microwave radiation increases, the displacement of the reservoir near the extraction well and the artificial prefabricated fracture changes more. It may be due to the microwave effect that the temperature of the reservoir rises, which affects the change of geostress. At the same time, the vibration effect brought by microwaves is also a factor that affects the displacement of the reservoir. The artificial fracture reduces the resistance of the overall displacement of the reservoir, which causes a larger displacement to occur near the extraction wells and the artificial fracture of the D place. Although the stress concentration phenomenon occurs near the microwave-generating wells, the displacement of the reservoir is overall movement, and the size of the wellhead is small compared to the reservoir, so there is no large displacement at point A near the microwave-transmitting wells.

Numerical simulation results of single steam heating

Single steam heating-temperature field

Figure 15 shows that the temperature of the reservoir increases gradually over time with the continuous injection of 650 °C high-temperature steam. The temperature rises from the vicinity of the wellhead outward. By 100 days, the average temperature exceeds 205 °C, and by 300 days, all areas of the reservoir reach over 420 °C, with an average temperature of 419 °C, indicating that the reservoir has undergone initial pyrolysis from the injection well to the surroundings. By 500 days, all areas of the oil shale reservoir are heated to over 500 °C, with the temperature around the injection wells maintained at 550 °C and an average temperature of 530 °C, indicating the start of secondary pyrolysis throughout the reservoir. By 700 days, the minimum temperature of the reservoir exceeds 600 °C. During heat transfer, the fractures in the reservoir can reach 630 °C by 1000 days. Heat loss during high-temperature steam heating of oil shale is mainly due to heat transfer into the surrounding mudstone. Initially, there is some heat loss around the wellhead, but it is relatively small. As heat injection time increases, heat loss gradually decreases, and the overall heating of the reservoir is not significantly impacted.

As can be seen from Fig. 16, the temperature of the reservoir under the action of water vapour increases with time and changes logarithmically. The temperature at point A, which is close to the injection wellhead, rises the fastest and reaches 350 °C at 100 days of water vapour injection. Meanwhile, the temperatures at observation points B, C, and D were around 245, 175, and 150 °C, respectively. This phenomenon is mainly due to the



Fig. 13. Reservoir displacement variation maps at 600 W.



Fig. 14. Trends of displacement at different locations.

fact that many fractures were created near the wellhead location during the drilling process. Under the water injection pressure, these fissures were rapidly connected and formed transportation channels, which caused the oil shale reservoir near the drilling well to warm up rapidly. As a result, the temperature at point A rises the fastest. As the range of water vapour flow expands, heat loss increases, so point C, which is farther away from the wellhead, warms more slowly.

On the other hand, observation point D, which is also affected by drilling and has many fissures, the water vapour that loses temperature is able to circulate rapidly in the section from C to D, which reduces the heat loss. Therefore, the warming curves of observation points C and D basically overlap. The temperature change curves of the four observation points gradually stabilize at 400 days.

Single steam heating-porosity and permeability

Figures 17 and 18 show that under the action of high-temperature steam, the reservoir forms a uniform pore network under high temperature and pressure. Initially, the pores connect gradually from the wellhead location to the surrounding area. By 600 days, when the temperature reaches 600 °C, the organic matter in the oil shale reservoir is almost completely pyrolyzed, and the pore network is fully connected. The connectivity of the internal pores in the oil shale enhances hydrocarbon transport within the reservoir and increases permeability.

Figure 19a shows that the porosity of the reservoir rapidly decreases and then increases in the first 75 days. The porosity near the injection well gradually decreases from the initial value of 5–2%. This may be due to water molecules within the rock moving to the reservoir pores and evaporating as the temperature increases in the initial heating stage, resulting in a decrease in pore space. The evaporation of water increases the effective stress in the pores, causing them to shrink and the porosity to decrease. However, as the temperature continues to rise, the water molecules inside the rock decompose and produce gases, such as water vapour and other gaseous substances. These gases fill the pores, gradually increasing porosity. This process is known as the water-locking effect, where the pore space to decrease initially and then increase during the heating process of oil shale reservoirs can be explained by the water-locking effect. Initially, the pore space decreases due to water evaporation, and then gas filling causes the pore space to increase. From 100 to 500 days, the porosity gradually increases with temperature. Compared to microwave heating, the porosity is more uniform. By 500 days, the porosity of all reservoirs reaches 18%, with an average porosity of 18.3%.

Meanwhile, the permeability shows significant variation with increased heating time, as shown in Fig. 19b From an initial permeability of 2.6×10^{-17} m² at 20 °C (room temperature), the permeability starts to rise rapidly when the temperature reaches 350 °C at 250 days, beginning first at probe point A, closest to the wellhead, followed by probes B, C, and D. This indicates that the oil shale reservoir began pyrolysis after 350 °C, with permeability increasing rapidly under pressure. The average permeability of the reservoir was 8.65×10^{-12} m² when the average temperature reached 500 °C at 450 days, showing significant changes under high-temperature steam. The permeability continues to increase and then levels off after 500 °C. The average permeability of the oil shale reservoir reaches 2.9×10^{-11} m² when the average temperature reaches 600 °C at 900 days.

Single steam heating-displacement field

As shown in Fig. 20, similar to the displacement field of microwave heating, the displacement field of the reservoir heated by high-temperature steam is primarily characterized by overall reservoir displacement, with the largest displacement occurring at the fissure. The increase in temperature leads to changes in the elastic modulus, and the pressure at the injection wellhead also influences the displacement of the reservoir. Under high-temperature steam injection, the average displacement of the reservoir was 3.1 cm at 500 days. At the



Fig. 15. 650 °C high-temperature steam heating temperature variation with time.

beginning of the heating period, the largest displacement change is observed at point D near the extraction well, with displacement changes decreasing at points C, B, and A as the distance from the extraction well increases. At 1000 days, the maximum displacement reaches 8.42 cm, and the average displacement is 3.8 cm.

As can be seen from Fig. 21, the displacement of the oil shale reservoir under the action of water vapour increases with the increase of heat injection time. Unlike the linear relationship of reservoir displacement with time under the action of microwave, the displacement of oil shale reservoir under the action of water vapour has a logarithmic relationship with time. Observation point A near the injection well has the smallest displacement, which is only 3 cm at 1000 days of water vapour injection, while observation point D near the artificial fissure



Fig. 16. Temperature variation at different locations.

has a larger displacement of 8.42 cm, which may be due to the fact that the pyrolysis of oil shale causes overall displacement. The creation of the artificial fissure leads to changes in the geostress, and the reservoir moves from the two sides toward the artificial fissure, resulting in a larger displacement near the extraction well. For the observation points near the injection wells, the injection of water vapour may have improved the bonding between the rock particles at the wellheads, which, together with friction, made the rocks near the wellheads more stable and less likely to be displaced.

Numerical simulation results of steam followed by microwave heating

Steam followed by microwave heating- temperature field

Considering the slow heating rate of steam and significant heat loss during heating, the steam heating of the oil shale was controlled for 300 days, allowing the average temperature of the reservoir to reach 350 °C, initiating the initial pyrolysis of the oil shale. Subsequently, microwave heating was applied for 200 days to rapidly increase the reservoir temperature and complete the secondary pyrolysis. Meanwhile, changes in the temperature field, porosity, permeability, and displacement field of the oil shale under the combined action of steam and microwave heating were studied.

When using the coordinated heating technology of steam followed by microwave to pyrolyze the oil shale reservoir, the initial steam heating stage concentrates high temperatures mainly in the wellhead area, with a small heating range. With the intervention of microwave heating, the high-temperature region significantly expands, resulting in more even and deeper heating of the entire reservoir, as shown in Fig. 22. At 300 days of steam heat injection, the highest temperature of the reservoir was 639 °C, concentrated near the wellhead. After the microwave effect, the highest temperatures of the reservoir at 400 and 500 days reached 784 and 922 °C, respectively, with the lowest temperatures being 506 and 647 °C, respectively.

Figure 23 shows the variation of the temperature field of the oil shale reservoir after 300 days of steam heating followed by 200 days of microwave heating. The temperature of the reservoir rises rapidly after 100 days of microwave heating, from an average temperature of 420–583.5 °C by the 400th day and to 725.66 °C by the 500th day, with the highest temperature reaching 922 °C. It can be seen that after high-temperature steam injection, microwave heating time. By the 450th day, the average temperature of the reservoir can reach 600 °C, achieving the temperature for complete pyrolysis of oil shale reservoirs. This is because the oil shale reservoir reaches the initial pyrolysis temperature of 350 °C after 300 days of high-temperature steam injection. The organic matter in the oil shale starts to soften and pyrolyze, forming pores under the pressure gradient, which increases the reservoir's permeability and allows water vapour to circulate smoothly. The high relative dielectric constant of water vapour rapidly increases the reservoir temperature after microwave application. It can be seen that the closer to the injection wellhead, the higher the temperature and the more sensitive the reservoir is to the combined action of steam and microwave.

Steam followed by microwave heating-porosity and permeability

As shown in Fig. 24, the reservoir pores become better connected after microwave action. The high relative permittivity of water vapour causes the reservoir temperature to increase rapidly under microwave action, leading to full pyrolysis of the organic matter. As a result, pore formation increases, and these pores connect to form a pore network, expanding the range of microwave action. The maximum porosity of the reservoir reaches 19.8% at 400 days and 20.7% at 500 days.

At the beginning of heating, probes A, B, C, and D all experienced changes in porosity, first decreasing and then increasing. Probe A started to increase rapidly after 25 days, while probes B, C, and D began to increase





after 100 days in a logarithmic manner, gradually flattening out over time. Porosity initially decreased and then increased with temperature, as shown in Fig. 25.

Figure 26 shows that the permeability of the reservoir under the effect of steam followed by microwave is increasing. The permeability range is significantly enhanced between 400 and 500 days, mainly centered on the wellhead and expanding in all directions from 1 to 400 days, with a clear demarcation line. By 500 days of steam injection, the permeability expansion of the reservoir is evident, with the average permeability reaching 1.738×10^{-11} m² and the permeability around the wellhead reaching 3.35×10^{-11} m². The permeability of the



Fig. 18. Permeability variation by steam heat injection at 650 °C.

four probes, A, B, C, and D, gradually increases with time. The closer to the injection well, the greater the permeability, as shown in Table 3.

Steam followed by microwave heating-displacement field

Under the action of steam followed by microwave heating, the initial displacement of the reservoir is small around the wellhead, gradually approaching the fracture location and showing overall movement. Between 100 and 400 days, the displacement mainly occurs around the fracture and gradually increases. By 500 days, the maximum displacement of the reservoir is 7.5 cm, with an average displacement of 3.38 cm. The displacement increases with temperature; displacement is logarithmic with time. Especially around 300 days when the heating mode shifts, causing a sudden rise in displacement. At 300 days, the time and displacement curves changed abruptly, which may be due to the effect of microwaves on the water vapour and water flowing in the reservoir,





due to the relatively high relative dielectric constants of water vapour and water, the high dielectric constants mean that the water molecules are highly susceptible to polarization reactions under the action of microwaves, resulting in violent rotation and vibration of the inner parts of the molecules, and this rapid movement in the form of friction or internal collisions, the Converts electromagnetic energy into thermal energy, causing the material to warm up quickly, but also causing the displacement pattern of the reservoir to change and undergo abrupt changes. Similarly, at observation point A near the injection wells, the reservoir displacement changes the least, while at observation point D near the extraction wells and artificial fissures, the displacement is the most, as shown in Figs. 27 and 28.

Numerical simulation results of microwave followed by steam

Microwave followed by steam heating-temperature field

Under the action of microwave followed by steam, the reservoir contracts significantly in the high-temperature region after steam application, with higher temperatures near the wellhead. Due to the microwave action, the reservoir near the injection wellhead undergoes pyrolysis, forming more pores that gradually connect to form a pore network, facilitating the circulation of high-temperature steam in the pores. Figure 29 shows that the reservoir is gradually heated to the fissure after steam application, resulting in more uniform heating. From different locations, point A near the wellhead has the fastest heating rate. The temperatures at points A, B, C, and D gradually increase, with the temperature curve tending to flatten out, as shown in Fig. 30.

Microwave followed by steam heating-porosity and permeability

After 300 days of microwave heating followed by steam heating, heat is primarily transferred from the injection wellhead to the surrounding area. It is evident that after steam injection, the porosity of the reservoir expands in all directions from the wellhead, with noticeable changes in porosity at the wellhead and gradual connection of similar wellheads, as shown in Fig. 31. From the porosity change curves at different locations, it is evident that probe A near the wellhead is most affected by the shift in heating mode, with a noticeable sudden change at 300 days, gradually flattening out. Probes B, C, and D, farther from the wellhead, are less affected and show a gentle upward trend. Porosity gradually increases with temperature, and the higher the temperature, the greater the change in porosity, as shown in Fig. 32.

In the initial stage of steam heating, following microwave action, the reservoir shows higher permeability around the injection wellhead, creating a significant permeability gradient compared to the surrounding area. The central area has much higher permeability than the edges, and the upper and lower wells on both sides of the fracture also exhibit significantly higher permeability due to the connectivity of the pore space, as shown in Fig. 33.

In the table of permeability changes at different locations, as shown in Table 4, the permeability of probe A is 1405 times that of probe D at 400 days, while at 500 days, probe A's permeability is 1315 times that of probe D, indicating that the permeability near the injection wells is much higher than that of the reservoir farther away.

Microwave followed by steam heating-displacement field

As shown in Fig. 34, the displacement of the reservoir under microwave followed by steam heating initially shows a small displacement around the wellhead. With increased heat injection time and temperature, the reservoir on both sides of the fissure moves toward the fissure, resulting in overall displacement. Between 100 and 400 days,



Fig. 20. Reservoir displacement variation maps at 650 °C steam.

displacement mainly occurs around the fissure and gradually increases. By 500 days, the maximum displacement of the reservoir is 5.51 cm, and the average displacement is 2.65 cm. As shown in Fig. 35, the displacement at probes A, B, C, and D initially increases with time, following a convex curve pattern. Due to the short duration of steam action, significant heat loss occurs during cooling condensation, resulting in a decrease in reservoir displacement. Additionally, after microwave heating, thermal stresses inside the rock may be released during steam heating, further decreasing displacement.









Comparative analysis of four heating methods

Temperature comparative analysis

Figure 36 shows that the temperature of oil shale reservoirs under the action of the four methods increases with time. The oil shale reservoir absorbs energy during the heating process, transferring internal heat through the oil shale skeleton via conduction. As temperature increases, the organic matter undergoes a phase change from a solid to a fluid form, which then flows to areas with lower temperature gradients through convection.

Among the four methods, the combination of steam followed by microwave heating shows the most significant warming effect, with the fastest warming speed and most uniform heating. Particularly, in the 200 days following the end of steam heating and the start of microwave heating at 300 days, the temperature change of the reservoir accelerates. By 500 days, the average temperature reaches 700 °C, and the reservoir is completely pyrolyzed. This is mainly because the microwave heating speed depends on the relative dielectric



Fig. 23. Temperature variation at different locations and average temperature variation.



Fig. 24. Steam followed by microwave porosity variation.

constant of the heating medium. The relative dielectric constant of oil shale itself is low. After steam heat injection, the reservoir is filled with water vapour and water, which have a high relative dielectric constant. This improves the efficiency of microwave heating, achieving rapid warming. Next is the single microwave heating effect. The average temperature of the reservoir reaches 570 °C after 500 days of heating, with the reservoir being almost completely pyrolyzed. Compared to the steam followed by microwave mode, the average temperature is lower and the heating is slightly uneven. Finally, the average temperature of the oil shale reservoir under single high-temperature steam and microwave followed by steam is 528.53 and 524.36 °C, respectively, after 500 days, which are similar. The difference is that the warming speed of a single high-temperature steam is higher in the first 300 days, then levels off in the next 200 days, likely due to large heat loss in the high-temperature steam reservoir. The farther from the injection wellhead, the more pronounced the temperature gradient, with lower temperatures farther away. High temperatures mainly occur near the wellhead, resulting in uneven heating. The









temperature over time shows a logarithmic relationship, consistent with Ma's⁴⁰ FLAC3D simulation results of oil shale formation temperature. The microwave followed by steam heating warms the reservoir gently in a linear manner for the first 400 days. The warming rate tends to flatten out after 400 days, resulting in more uniform heating compared to a single high-temperature steam injection.

Porosity comparative analysis

Figure 37 shows that the reservoir porosity under steam followed by microwave and single high-temperature steam methods first decreases and then increases within the first 100 days of heating. This may be because, in the initial heating stage, as the temperature rises, water molecules within the rock move to the reservoir pores and evaporate, leading to an initial decrease in pore space. Water evaporation increases the effective stress in the pore space, causing pore shrinkage and a decrease in porosity. Conversely, the reservoir porosity under a single

Various locations	Heating days (d)	Permeability(m ²)
	0	2.67×10^{-17}
	100	2.4664×10^{-14}
\mathbf{D} rehation $(45.8.6)$	200	1.5419×10^{-13}
F100e A (4.5, 8.0)	300	1.1043×10^{-11}
	400	2.3593×10^{-11}
	500	2.6464×10^{-11}
	0	2.67×10^{-17}
Probe B (5.5, 7.8)	100	3.685×10^{-15}
	200	8.765×10^{-15}
	300	1.3808×10^{-13}
	400	1.8312×10^{-13}
	500	2.2703×10^{-11}
	0	2.67×10^{-17}
Probe C (6.5, 7.1)	100	2.2045×10^{-15}
	200	6.889×10^{-15}
	300	1.1559×10^{-13}
	400	1.6529×10^{-13}
	500	2.1215×10^{-11}
	0	2.67×10^{-17}
	100	1.7368×10^{-15}
Probe D (7 5 6 3)	200	6.215×10^{-15}
(7.5, 0.5)	300	8.192×10^{-14}
	400	1.5853×10^{-13}
	500	1.7888×10^{-11}





Fig. 27. Reservoir displacement variation under steam followed by microwave.



Fig. 28. Trends of displacement at different locations.





microwave and microwave followed by steam heating shows a linear increasing trend. Overall, the porosity under all four heating methods shows an increasing trend and gradually levels off.

Among the four methods, the porosity growth effect under steam followed by microwave heating is the most significant, with the fastest increase rate between 100 and 400 days, and the porosity levels off between 400 and 500 days. At 500 days, the maximum porosity is 21%, and the average porosity is 19.52%. This is due to the rapid warming of the reservoir by steam followed by microwave heating, which causes rapid pyrolysis of the organic matter, forming pores under pore pressure and high-temperature steam, and connecting to the pore network.

Additionally, the porosity distribution of the reservoir under steam followed by microwave heating is more uniform. The next most uniform distribution is under the action of 650 °C high-temperature steam. When steam is injected for 300 days, the average porosity is 15%, leveling off, and the highest porosity reaches 19% at



Fig. 30. Temperature variation at different locations and average temperature variation.





500 days with an average porosity of 18.7%, second only to the steam followed by the microwave method. The porosity distribution of the reservoir under microwave followed by steam heating is more uniform. After 600 W microwave heating, the porosity growth rate between 300 and 500 days is higher than between 1 and 300 days, showing better growth than single 600 W microwave heating. The maximum porosity at 500 days is 19%, and the average porosity is 17.74%, indicating that high-temperature steam injection after microwave heating can effectively connect the pores formed by microwave pyrolysis. The porosity did not level off after 200 days but continued to grow rapidly. The porosity is expected to reach the maximum value of the four pyrolysis methods by 550 days. The change in porosity with single microwave heating is significant in the early stage, especially within the first 1–200 days, with the fastest growth among the four methods. However, the growth rate remains unchanged over time, and porosity formation and connectivity mainly occur around the wellheads, resulting in a noticeable porosity gradient and poorer connectivity compared to the other methods.

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Fig. 33. Microwave followed by steam permeability variation.

Permeability comparative analysis

Figure 38 shows significant differences in the permeability performance of the formation under the four heating methods. Around the injection well, the porosity of the oil shale increases greatly due to high temperatures, and thermal rupture is very obvious. Consequently, the permeability of the formation is better near the wellhead. However, near the extraction well, although the temperature of the oil shale increases, its physical structure has not changed much compared to the room temperature state, resulting in still poor permeability and incomplete seepage channels.

Over time, the temperature of the reservoir continued to increase, significantly improving the permeability near the oil extraction wells. This is consistent with Lei's⁴¹ simulation results of in-situ oil shale pyrolysis and Liu's⁴² tests on the permeability of Jimushar oil shale in Xinjiang at a burial depth of 400 m. Liu concluded that the permeability increase of oil shale is small between 200 and 300 °C, which is consistent with the conclusions

Various locations Heating days(d)		Permeability(m ²)
	0	2.67×10^{-17}
	100	1.0911×10^{-16}
Probe A (4.5, 8.6)	200	1.9136×10^{-16}
	300	3.0346×10^{-16}
	400	2.2437×10^{-11}
	500	2.3695×10^{-11}
	0	2.67×10^{-17}
	100	6.4844×10^{-17}
Probe P(55.78)	200	1.2125×10^{-16}
Probe B (5.5, 7.8)	300	2.0211×10^{-16}
	400	1.8×10^{-14}
	500	1.9822×10^{-11}
	0	2.67×10^{-17}
Probe C (6.5, 7.1)	100	4.9883×10^{-17}
	200	9.5692×10^{-17}
	300	1.6415×10^{-16}
	400	1.6529×10^{-14}
	500	1.8516×10^{-14}
	0	2.67×10^{-17}
	100	4.4755×10^{-17}
Probe $D(75,63)$	200	8.6407×10^{-17}
F100e D (7.3, 0.3)	300	1.5011×10^{-16}
	400	1.5961×10^{-14}
	500	1.8008×10^{-14}

Table 4. Variation in permeability by location.



Fig. 34. Reservoir displacement variation under microwave followed by steam.



Fig. 35. Trends of displacement at different locations.



Fig. 36. Variation of reservoir temperature at different modes of action.

in this paper. The permeability improvement of Xinjiang Jimusaer oil shale is notable in the temperature range of 300–350 °C.

In this case, the permeability under single microwave heating grew slowly, with a maximum average of 7.74×10^{-16} m² and an average permeability of 4.343×10^{-16} m² in the reservoir at 500 days, which is only a 16-fold increase compared to the initial 2.67×10^{-17} m². The permeability distribution map shows that the permeability mainly expanded in a small area around the injection well.

The permeability under single high-temperature steam, microwave followed by steam, and steam followed by microwave actions showed significant growth. The largest average permeability at 500 days was 2.05×10^{-11} m² after a single high-temperature steam action, which is 7.6×10^5 times the initial permeability. The permeability distribution is more uniform and circulates widely around the four wellheads. The average permeability under steam followed by microwave action is 1.738×10^{-11} m², 6.5×10^5 times the initial permeability, showing the best uniformity in distribution among the four methods. The four injection wells are gradually connected, mainly due to the reservoir's improved pore connectivity under steam followed by microwave action. Finally, the average permeability under microwave followed by steam is 1.09×10^{-11} m², 4.08×10^5 times the initial permeability.



Fig. 37. Variation of reservoir porosity at different modes of action.



Fig. 38. Variation of reservoir permeability at different modes of action.

Displacement comparative analysis

Figure 39 shows the variation and distribution of reservoir displacement under the four heating methods. The displacement increases under single microwave heating, single high-temperature steam heating, and steam followed by microwave heating. However, under microwave followed by steam heating, the displacement shows an upward and then downward trend between 400 and 500 days. The displacement distribution is consistent across the four methods, with the largest displacement at the four injection wellheads due to stress concentration from drilling, which reduces the cross-sectional area and increases stress. At 500 days, the largest average displacement is observed under steam followed by microwave heating, with a maximum displacement of 7.5 cm and an average displacement of 3.38 cm. This indicates that under microwave heating, high-frequency resonance causes water molecules to produce friction and collision, affecting reservoir displacement is significant, with average displacements of 3.3 and 3.11 cm, respectively, at 500 days of heating. The displacement gradually flattens out over time under single high-temperature steam heating but maintains a linear upward trend under microwave heating. The reservoir displacement under microwave followed by steam heating shows a shrinking



Fig. 39. Variation of reservoir displacement at different modes of action.

trend at 450 days. This may be due to the penetration effect of steam heating and the release of internal thermal stresses in the rock during steam heating after microwave heating, resulting in reduced displacement.

Comparison analysis of traditional heating and synergistic heating

To better understand the advantages of oil shale reservoir changes under the synergistic heating and traditional heating modes adopted in this paper, the numerical simulation results of five modes, i.e., electric heating, steam heating, microwave heating, steam followed by microwave heating, and microwave followed by steam heating, were used for comparative analyses. Due to the varying scales of oil shale reservoirs, different well deployment strategies, and initial test values in numerical simulations, making comparative analyses under uniform conditions is challenging. Based on results obtained by Wang¹⁹ through numerical simulations and comparative analyses of electric and steam heating, it was found that in a similarly scaled oil shale reservoir, insitu steam injection technology requires 3.5 years to heat the reservoir to 500 °C. In contrast, the in-situ heating technology using ICP point well deployment takes 10 years to reach the same temperature in the extraction area. This indicates that the heating efficiency of in-situ steam injection technology is significantly higher. Based on this, we can conclude that the in-situ steam extraction method of oil shale is better than the electric heating extraction method. According to the results of numerical simulation in this paper, under the same scale, the cycle time required for heating the oil shale reservoir to 600 °C steam injection is 767 days, the number of days needed for microwave heating is 530 days, the number of days required for the coordinated action of steam followed by microwave is 442 days, and the number of days needed for the coordinated action of microwave followed by steam is 620 days, which can be seen that the coordinated action of oil shale reservoir under the coordinated action of steam followed by microwave is shorter than the cycle time required. Taken together, the synergistic heating method of oil shale extraction may be more advantageous than traditional electric heating, steam heating, and microwave heating.

Comparative analysis of actual engineering significance

Based on the numerical simulation results, an analysis considering operating costs, environmental issues, and feasibility under four methods was conducted, using a final decomposition temperature of oil shale at 600 °C as the boundary. The numerical simulation results for the four heating modes are as follows: 600 W microwave heating requires 530 days, 650 °C steam heating requires 767 days, initially using 650 °C steam heating followed by 600 W microwave heating requires 442 days, and initially using 600 W microwave heating followed by 650 °C steam heating requires 620 days. Firstly, considering the required heating period, the heating effect of the reservoir is best under steam followed by microwave mode, followed by 600 W microwave mode, microwave followed by steam mode, and steam mode. Regarding the operating costs of the four methods, based on the numerical simulation model of an oil shale reservoir measuring 16 m×12 m×10 m containing 3840 tons of oil shale, the daily electricity consumption for 600 W is 14.4 kW h. Heating oil shale to 600 °C with a 600 W microwave requires 530 days. Using the industrial electricity price in China of 0.7 yuan/(kW h), the electricity cost for 600 W microwave in situ exploitation is 21,369.6 yuan. If a high-temperature steam boiler utilizes the most basic coal energy, with coal priced at 400 yuan per ton and energy content of 20.93×10^{6} J/kg⁴³, the steam boiler, assuming a 0.2 MV capacity, requires 0.04 tons of coal daily. Heating the oil shale reservoir to 600 °C using steam requires 767 days, resulting in a coal cost of 12,272 yuan. Similarly, the costs for the steam followed by microwave mode and the microwave followed by steam mode in terms of electricity and coal consumption are 10, 525 yuan and 17, 216 yuan, respectively. In summary, in terms of the heating period, steam followed by microwave < single microwave heating < microwave followed by steam < single steam heating. Regarding the costs, steam followed by microwave < single steam heating < microwave followed by steam < single microwave heating.

Analyse these four types of heating in terms of the environment. For microwave heating the impact of microwave heating on the environment is relatively small, but from the results of numerical simulation, microwave heating may cause ground subsidence and reservoir displacement, and microwave radiation will have a certain impact on the organisms within the microwave radiation range. The use of water vapour pyrolysis of oil shale may also cause ground subsidence and reservoir displacement due to the change of reservoir structure, as well as groundwater contamination due to the injection of water vapour. The use of steam followed by microwave heating will result in greater vibration under microwave action due to the high relative dielectric constants of steam and water, leading to more severe ground subsidence and displacement, as well as contamination of groundwater. The use of microwave followed by steam heating will result in less ground subsidence and displacement of the reservoir, which will also pollute the groundwater to a certain extent. Therefore, the environmental impact of these four methods is much smaller than that of traditional heating modes, such as ground distillation, combustion heating, and electric heating.

Analyse these four heating methods in terms of feasibility. The technology of water vapour pyrolysis of oil shale has completed small-scale testing in the laboratory. Still, due to the long cycle time of water vapour pyrolysis of oil shale, experiments in the field have yet to be carried out. The technology of microwave pyrolysis of oil shale hinders the feasibility of the method because it consumes a large amount of electrical energy, which leads to a high cost of development. Steam followed by microwave technology is a multi-modal extraction model that only requires the addition of a microwave generator after water vapour injection, which can greatly shorten the cycle time and likewise reduce the amount of electrical energy consumed by a single microwave action, making it more feasible. Microwave followed by steam technology is also a multi-mode mining mode, which can avoid the water lock effect produced by the reservoir under the action of water vapour and reduce the waste of energy consumption, which also has a certain degree of feasibility.

Conclusion and prospect

Conclusion

A coupled electromagnetic-thermal-fluid-solid model was established using COMSOL Multiphysics software, and numerical simulations of 600 W single microwave pyrolysis of oil shale, 650 °C high-temperature steam pyrolysis of oil shale, and the pyrolysis process under the synergistic effect of steam and microwave were carried out in conjunction with mathematical models of oil shale pyrolysis to reach the following conclusions:

- (1) The temperature increased with the duration of heat injection for all four methods. Among them, the steam followed by microwave in-situ extraction technology exhibited the fastest heating rate and the most uniform heating effect. This technique leverages the high relative dielectric constant of injected water steam to achieve rapid warming under microwave action, compensating for the limited range of single microwave heating and shortening the cycle of high-temperature steam in-situ extraction. Consequently, kerogen reaches pyrolysis temperature (about 400 days) significantly faster than with the other three methods.
- (2) Different heating methods significantly affect reservoir porosity. The single high-temperature steam and steam followed by microwave modes show a decreasing and then increasing porosity trend due to the water-lock effect, while the other two modes show continuous porosity increases with heating time. The steam followed by microwave in-situ extraction technology exhibits the best porosity connectivity among the four heating methods, with an average porosity of 19.5%, an increase of 14%, and a wider connectivity range of pores. Although it is not as effective as single high-temperature steam pyrolysis in the connectivity range, the difference is minor. Therefore, the steam followed by the microwave method is superior to the other three methods for expanding reservoir porosity.
- (3) Permeability increased slowly at the beginning of heat injection but increased significantly after 250 days. The single high-temperature steam and steam followed by microwave heating modes significantly increased reservoir permeability, reaching 7.6 × 10⁵ and 6.5 × 10⁵ times the initial permeability at 500 days, respectively. In contrast, permeability increase from single microwave heating was slower due to the smaller range of microwave action, limiting its effect on more distant reservoirs. At 500 days, the maximum average permeability of the reservoir was 7.74 × 10⁻¹⁶ m² and the average permeability was 4.343 × 10⁻¹⁶ m², which is only a 16-fold increase from the initial permeability of 2.67 × 10⁻¹⁷ m². Therefore, single high-temperature steam and steam followed by microwave methods significantly affect the permeability of oil shale reservoirs.
- (4) Different heating methods cause relative displacement of oil shale reservoirs, mainly manifesting as overall displacement toward the fracture. The displacement under steam followed by microwave is the largest, with a maximum displacement of 7.5 cm and an average displacement of 3.38 cm. Displacements under single heating methods have different trends over time. Displacement under single high-temperature steam heating gradually flattens out, while displacement under single microwave heating maintains a linear upward trend. Displacement under microwave followed by steam shows an increasing and then decreasing trend. The reservoir displacement is the smallest, with a maximum displacement of 5.51 cm at 500 days and an average displacement of 2.65 cm. This shows that microwave followed by steam has the smallest effect on reservoir displacement, outperforming the other three methods.
- (5) Through the cost analysis, environmental impact and feasibility study, based on the results of numerical simulation, it is concluded that the cost of in-situ extraction of oil shale with a size of $16 \text{ m} \times 12 \text{ m} \times 10 \text{ m}$, in-situ extraction by steam followed by microwave is 10,525 yuan, the cost required for single steam heating is 12,272 yuan, the cost required for microwave followed by steam heating is 17,216 yuan, and the cost required for single microwave heating is 21,369.6 yuan, indicating that the steam followed by microwave

approach is the least in terms of cost, followed by water vapor injection heat mining, followed by microwave followed by steam action, and single microwave heating requires the most cost. Environmentally, all four methods cause ground subsidence, while the water vapor heat injection and synergistic action methods also cause groundwater contamination problems. All four modes have better feasibility, but in terms of the development cycle, steam followed by microwave mode is the shortest and most feasible to extract oil shale.

Comparative analysis of temperature, porosity, permeability, and displacement of oil shale reservoirs using different heating methods in conjunction with cost, environmental impact, and feasibility studies concluded that steam and microwave technologies are the most effective for pyrolysis of oil shale reservoirs, surpassing the other three methods.

Prospect

Although we have solved most of the problems in the numerical simulation of in situ oil shale extraction under the four extraction methods, there are still many unattainable goals for some issues, such as the potential problems of the COMSOL Multiphysics numerical simulation software that we have used and the limitations of the experiments.

Some of the potential problems with using COMSOL Multiphysics and the steps we have taken to minimise errors can provide valuable suggestions for future researchers. For example, (1) COMSOL's numerical solution process may introduce biases due to rounding and truncation errors, especially when dealing with very large or very small values. For this reason, we can select the double-precision calculation option during the solving to ensure the accuracy of the numerical solution. (2) Different versions of the software may have changes in functionality, algorithms, or interface, which may lead to different results for the same model in different versions. For this reason, we can test the model in different versions to ensure that the effect of version change on the results is controllable. (3) The default setting of the multi-field coupling model has some deviation from the experimentally fitted multi-field coupling model, which leads to errors in the simulation results. For this reason, we need to change the default settings or optimise the process to reduce the error.

As for the limitation of experimental conditions, our self-developed equipment is unable to test oil shale specimens with high axial, circumferential pressure and large specimens to get the research data more in line with the real reservoir conditions, so the results have certain limitations and cannot avoid the errors of experimental results. At the same time, the mathematical formula used in the article for the synergistic effect of steam and microwave comes from our team's experiments on microwave action on oil shale and other scholars' experiments on thermal extraction of oil shale by high-temperature water vapour. We did not get the real experimental data on oil shale under the synergistic effect of microwave and steam, so there may be some deviations between the model used and the model fitted to the real experimental data, which will be used by our research and development equipment for more in-depth research and development work in the future. We will carry out more in-depth research and development equipment for microwave and steam are more real and perfect.

The In-situ pyrolysis method of oil shale under the coordinated action of microwave and steam is a multidisciplinary, cross-complex problem. At the same time, it also breaks the confinement of a single mode of exploitation of in-situ pyrolysis of oil shale, which provides a good idea for the future cross-application of various modes. This research will provide valuable information on the high efficiency of exploitation of oil shale. However, in view of the complexity of in situ pyrolysis by synergistic action of microwave and steam, it is necessary to start from the following aspects in the future:

- (1) The mathematical formula under the synergistic effect of microwave and steam simulated in this paper is the result of our team's experiments on oil shale through microwave action and other scholars' experiments on thermal extraction of oil shale through high-temperature water vapour. We have yet to obtain the real experimental data of oil shale under the synergistic effect of microwave and steam. We will first carry out experimental verification of the numerical simulation results by using self-developed equipment in our future work. After the experimental validation, we will analyse the experimental data in detail to optimise the accuracy of the mathematical model. Then, we plan to explore the effects of different combinations of microwave power and steam parameters on oil shale extraction efficiency.
- (2) In this paper, the simulation of the synergistic effects of microwave and steam does not account for the kinetic reactions of solid components or the influence of chemical reactions on porosity and permeability. This is because the microwave steam synergistic pyrolysis of oil shale technology involves a complex multi-field coupling relationship, which contains electromagnetic-thermal-fluidic-solid-chemical and another multi-field coupling, and at the same time, lacks the relevant experimental data and the support of the fitted relationship so that the chemical reaction and other reservoir change reactions are not taken into account. However, other changes in oil shale reservoirs under the synergistic effect of microwave and steam are undeniable, so more in-depth research should be carried out on the synergistic pyrolysis of oil shale by microwave and steam in the future.
- (3) In the simulation of in-situ pyrolysis of oil shale reservoirs in this paper, only the isotropy and modulus of elasticity of oil shale, porosity, and thermal conductivity are considered. The reservoir's anisotropy should be considered in future simulations, and the influence of other physical mechanics parameters on the reservoir should be explored.
- (4) Improvement of the model of energy migration and transformation of rock samples in the process of microwave radiation synergistic steam heat injection based on the electromagnetic-thermal-fluid-solid coupling model.

(5) Considering the changes in oil shale reservoirs under the simultaneous action of microwave and steam, a large-scale oil shale layer similar model was mounted. An industrial steam generator and a microwave antenna were used to conduct the hot steam and microwave energy into the rock samples simultaneously and to study their thermal evolution process.

Data availability

The data that support the findings of this study are available from the author upon reasonable request. Data For any data or related questions mentioned in the paper, please contact the second author Yinlong Zhu or the first and corresponding author Yao Cheng. E-mail address: 320976492@qq.com (Yinlong Zhu) E-mail address: yaoyao9873@163.com (Yao Cheng).

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Y.C.: Conceptualization, Formal Analysis, Supervision, Validation, Investigation, Writing-original draft, Writing-review & editing. Y.Z.: Conceptualization, Data curation, Software, Investigation, Methodology, Writing-original draft, Writing-review & editing. L.Z.: Software, Methodology, Visualization. M.Y.: Conceptualization, Supervision, Writing-original draft, Writing-review & editing.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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