Analysis of the Influence of Fracture Morphology on Oil Shale Formation Pyrolysis under In Situ Heat Injection Mining (Postprint)

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Abstract

To address the unresolved issue of how fracture morphology influences reservoir pyrolysis during in-situ thermal injection production of oil shale, which hinders accurate assessment of actual pyrolysis efficiency, this study takes the Fushun oil shale reservoir as the research object and employs a numerical simulation approach to establish a coupled thermal-hydraulic-mechanical numerical model. The reliability of the model is verified, and the differences in the thermal injection production process for two types of oil shale fractures (hydraulic fractures and bedding-parallel fractures) are investigated. The temporal evolution laws of reservoir temperature, steam injection pressure, vertical formation displacement, and the temperature of overlying and underlying strata with thermal injection time are obtained. The results show that, in the case of bedding-parallel fractures, multiple pyrolysis pathways exist in the oil shale reservoir, whereas in the case of hydraulic fractures, the oil shale reservoir undergoes uniform pyrolysis through a reticulated high-temperature channel. Compared with bedding-parallel fractures, hydraulic fractures exhibit better connectivity, and the average temperature of the oil shale layer can reach the temperature required for organic matter pyrolysis within only 50 days. After the end of production, the maximum vertical displacements of the formation in the bedding-parallel fracture model and the hydraulic fracture model are 0.14 m and 0.12 m, respectively, and the closer the rock layer is to the thermal injection well, the greater its vertical displacement. Due to the heat dissipation from the oil shale layer, the areas of the high-temperature region (>100 ℃) formed in the overlying and underlying strata are 521.11 m^2 and 650.93 m^2, respectively, indicating that more heat is lost in the hydraulic fracture model. During field in-situ thermal injection production of oil shale, it is necessary to reasonably adjust the thermal injection duration and keep hydraulic fractures away from the upper and lower boundaries of the oil shale reservoir to avoid dissipation of heat from high-temperature, high-pressure steam.

Full Text

Effect of Fracture Morphology on Oil Shale Layer Pyrolysis Under In-Situ Thermal Injection Mining

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Abstract

The influence of fracture morphology on reservoir pyrolysis during oil shale in-situ thermal injection mining remains unclear, making it difficult to accurately assess actual pyrolysis efficiency. Taking the Fushun oil shale reservoir as the research object, this study employs numerical simulation methods to establish a thermal-fluid-structure coupling numerical model for two fracture morphologies (hydraulic fracturing fractures and parallel bedding fractures). The model' s reliability is verified, and the differences in the injection mining processes are investigated to obtain the variation laws of reservoir temperature, steam injection pressure, vertical formation displacement, and upper/lower formation temperatures with injection time.

The results show that: (1) In parallel bedding fractures, multiple pyrolysis paths exist in the oil shale reservoir, whereas in hydraulic fracturing fractures, the reservoir undergoes uniform pyrolysis based on a network of high-temperature channels; (2) Hydraulic fracturing fractures exhibit better connectivity compared to parallel bedding fractures, requiring only 120 days for the average temperature of the oil shale layer to reach the temperature required for organic matter pyrolysis; (3) After mining, the maximum vertical displacements of the formation in the parallel bedding fracture and hydraulic fracturing fracture models are 0.14 m and 0.12 m, respectively, with greater vertical displacement observed in rock layers closer to the injection well; (4) Due to heat dissipation from the oil shale layer, the high-temperature (>100°C) area formed in the upper and lower formations is 650.93 m^2 and 521.11 m^2, respectively, with the hydraulic fracturing fracture model experiencing greater heat loss.

During on-site oil shale in-situ thermal injection mining, it is necessary to reasonably adjust the injection duration and keep hydraulic fractures away from the upper and lower boundaries of the oil shale reservoir to avoid dissipation of high-temperature, high-pressure steam energy.

Keywords: oil shale; in-situ thermal injection mining; fracture morphology; parallel bedding fractures; hydraulic fracturing fractures

1. Introduction

As a non-renewable energy source, petroleum faces continuously decreasing supply and increasing costs due to rapid societal development. Consequently, unconventional oil and gas resources such as shale gas and oil shale have attracted significant attention worldwide. Global proven oil shale reserves are substantial, with China' s proven oil shale resources ranking second in the world. Conventional oil shale extraction primarily relies on surface retorting methods, which are unsuitable for deeply buried oil shale and generate environmentally hazardous waste residues that are difficult to dispose of. In-situ conversion technology represents an emerging extraction method that offers environmental benefits and low costs, positioning it as the primary future approach for oil shale mining.

The oil shale in-situ conversion technology using high-temperature, high-pressure steam convection heating (MTI) is particularly suitable for Chinese oil shale reservoirs. This process requires hydraulic fracturing to create numerous interconnected fractures in the reservoir. However, hydraulic fracture propagation is complex, while new fractures generated during oil shale pyrolysis predominantly align with bedding planes. The variation laws of reservoir temperature, formation settlement, and temperature-affected zones in overlying and underlying rocks during in-situ thermal injection are critical prerequisites for successful field application.

Current numerical simulation research on oil shale in-situ conversion primarily focuses on conduction heating, electric heating, and microwave heating. Electric heating, essentially a conduction method, suffers from low heating rates and slow reservoir temperature rise, resulting in long mining durations. Microwave heating, fundamentally a radiation method, involves immature technology. In contrast, steam injection technology can effectively improve heating rates while carrying pyrolysis products to production wells. Previous studies have investigated anisotropic permeability effects, effective pyrolysis zone evolution, temperature distribution and permeability variation during pyrolysis, and pore structure evolution under different heating modes. However, existing numerical simulations mainly concentrate on injection duration and seepage field effects, lacking comparative studies on how different fracture morphologies influence the pyrolysis process.

Since in-situ thermal injection mining relies primarily on fractures as seepage channels for rapid reservoir heating and determines heat loss at reservoir boundaries, this study takes the Fushun oil shale reservoir as the research object. Using numerical simulation methods, a thermal-fluid-structure coupling model is established to compare two fracture morphologies (hydraulic fracturing fractures and parallel bedding fractures), verify model reliability, and investigate differences in the mining processes to obtain variation laws of reservoir temperature, steam pressure, and formation settlement with injection duration. The simulation results provide scientific reference for Fushun oil shale in-situ thermal injection mining.

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2. Model Establishment and Parameter Settings

2.1 Random Fracture Generation This study employs the Monte-Carlo method for random fracture simulation, based on the law of large numbers in probability theory. The generation process involves:

1. Determining the fracture generation domain and required physical parameters
2. Randomly generating point sets and sampling to obtain fracture parameters (aperture, location) at each point
3. Calculating fracture endpoint coordinates based on parameters and known point positions
4. Iteratively repeating these steps to generate multiple random fractures
5. Adjusting generated endpoint coordinates to match actual field distributions
6. Visualizing the random fracture network using plotting tools

2.2 Geometric Model Numerous uncontrollable factors exist in oil shale in-situ thermal injection mining. To simplify the numerical model and achieve better simulation results, the following assumptions are made:

- Chemical reactions during pyrolysis are ignored
- Heat transfer occurs primarily through convection heating, with thermal radiation neglected
- High-temperature, high-pressure steam flows consistently from injection to production wells
- Dynamic viscosity does not vary with temperature
- Steam and rock temperatures are equal at any given location
- The entire model represents a continuous medium

Using Fushun oil shale as the engineering background, the model consists of a 25 m thick oil shale layer with mudstone roof and floor. Randomly generated hydraulic fractures and parallel bedding fractures are included in the oil shale layer. The numerical simulation model has injection and production wells at 15 m depth, with top stress boundary σy = -5 MPa, bottom constrained, and side stress boundaries σx = -(6+α) MPa.

2.3 Governing Equations **Stress Field Equation:**

$$\sigma_{ij,j} + F_i = 0$$

where σ_{ij} is the stress tensor and F_i is body force (MPa).

Seepage Field Equation:

$$\frac{\partial(\rho_w S_w)}{\partial t} + \nabla \cdot (\rho_w \mathbf{v}) = q_m$$

Figure 4

Figure 1: Figure 4

$$\mathbf{v} = -\frac{k}{\mu}\nabla p$$

where ρ_w is water density (kg/m^3), S_w is water saturation, $\mathbf{v}$ is flow velocity (m/s), q_m is source/sink term, k is permeability, μ is dynamic viscosity (Pa • s), and p is pressure.

Temperature Field Equation:

$$\rho_m c_p \frac{\partial T}{\partial t} + \rho_w c_{pw} \mathbf{v} \cdot \nabla T = \nabla \cdot (\lambda \nabla T) + q_T$$

where ρ_m is matrix density (kg/m^3), c_p is specific heat capacity, T is temperature, λ is thermal conductivity, and q_T is heat source.

Coupling Relationship: The relationship between seepage and stress is given by:

$$k = k_0 e^{-\alpha \sigma_n}$$

where k is fracture permeability coefficient, k_0 is initial permeability, σ_n is normal stress on fracture surface, and α is coupling coefficient.

2.4 Model Reliability Verification To verify the thermal-fluid-structure coupling model, a three-dimensional dual-fracture injection model is simplified to a two-dimensional model of identical dimensions. The calculated variation law of average reservoir temperature with time shows a maximum calculation error of 3.94% during mid-term injection, demonstrating that the numerical model accuracy meets the requirements for oil shale in-situ thermal injection mining simulation.

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3. Simulation Results and Analysis

3.1 Temperature Distribution During Injection The heating rate during oil shale pyrolysis primarily depends on reservoir permeability. During convective heating, steam moisture condenses on rock surfaces, generating enormous expansion stresses that increase pore and fracture quantities, thereby enhancing permeability and connectivity.

Temperature variation patterns in both fracture models are shown in

. In the parallel bedding fracture model, steam flows rapidly along fractures, forming several narrow primary pyrolysis paths. Since matrix permeability is much lower than fracture permeability, the regions between primary paths heat slowly, with limited heat loss in nearby upper/lower formations. In contrast,

Figure 5

Figure 2: Figure 5

the hydraulic fracturing fracture model provides dense, well-connected pathways for steam migration, creating a network of high-temperature zones that expand uniformly across the reservoir.

At 365 days, most regions in both models reach pyrolysis temperature (400-500°C). The hydraulic fracturing model shows more uniform temperature distribution with only small areas near production wells remaining below pyrolysis temperature, while the parallel bedding model exhibits multiple distinct pyrolysis paths with slower inter-path heating.

Average temperature variation with injection time (

) reveals that hydraulic fracturing fractures reach pyrolysis temperature in only 120 days due to superior connectivity and permeability, enabling rapid whole-layer heating and reducing mining time and costs.

3.2 Steam Pressure Distribution During Injection Prior to injection, hydraulic fracturing creates fractures that enhance reservoir permeability. During injection, pyrolysis products increase formation pressure. In parallel bedding fractures ([FIGURE:6a]), pressure propagates primarily along layer directions, forming several high-pressure zones with distinct advance fronts. In hydraulic fracturing fractures ([FIGURE:6b]), interconnected fractures create uniform pressure gradient zones without obvious advance fronts, enabling more synchronous steam invasion throughout the reservoir.

Pressure distribution patterns indicate that hydraulic fracturing fractures provide more uniform steam migration pathways, while parallel bedding fractures exhibit pressure advance along primary channels with lagging peripheral heating.

3.3 Vertical Displacement Variation During Injection Vertical displacement evolution is shown in [FIGURE:7] and [FIGURE:8-10]. During initial injection (0-40 days), only minor displacement occurs in corner regions. As injection continues, thermal-stress coupling causes significant expansion deformation in upper/lower formations near injection and production wells. The average and maximum vertical displacements increase with injection time, with hydraulic fracturing fractures showing more uniform displacement distribution.

Final displacements reach 0.0402 m average and 0.1023 m maximum for parallel bedding fractures, and 0.038 m average and 0.12 m maximum for hydraulic fracturing fractures. Displacement growth rates slow after 50 days as most pyrolysis completes and multi-physics effects diminish.

3.4 Surrounding Rock Temperature Variation During Injection Temperature-affected areas in overlying and underlying formations are shown in [FIGURE:11-14]. For parallel bedding fractures, post-injection high-temperature (>100°C) areas measure 650.93 m^2 in overlying rock and 521.11 m^2 in floor rock. For hydraulic fracturing fractures, these areas are larger at 750 m^2 each, with more extensive high-temperature zones across all temperature intervals.

The greater heat loss in hydraulic fracturing models results from better fracture connectivity providing pathways for steam to contact surrounding rocks. In both models, floor rocks show larger high-temperature areas than overlying rocks due to gravity causing heat accumulation at the bottom.

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4. Conclusions

Based on field data from Fushun oil shale mining, this study of fracture morphology effects on pyrolysis yields the following conclusions:

1. **Connectivity Advantage**: Hydraulic fracturing fractures exhibit superior connectivity compared to parallel bedding fractures. High-temperature, high-pressure steam rapidly fills the entire reservoir, accelerating mining progress. The average reservoir temperature reaches pyrolysis temperature in only 120 days.
2. **Displacement Patterns**: During in-situ thermal injection, rock layers closer to injection wells experience greater vertical displacement. After complete pyrolysis, average vertical displacements are 0.05 m and 0.038 m for parallel bedding and hydraulic fracturing fracture models, respectively.
3. **Heat Loss**: The hydraulic fracturing fracture model shows 10.07% larger temperature-affected areas in surrounding rocks than the parallel bedding fracture model. Post-injection, the affected area S is 8.7% larger, indicating greater heat loss.
4. **Engineering Recommendation**: During hydraulic fracturing operations, fractures should be appropriately distanced from roof and floor rocks to prevent excessive heat loss from high-temperature, high-pressure steam dissipation.

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Figure 1

Figure 3: Figure 1

Figure 2

Figure 4: Figure 2

Figures

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Figure 8

Figure 5: Figure 8

Figure 12

Figure 6: Figure 12

Figure 13

Figure 7: Figure 13