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Review and outlook on the application of thermal-hydraulic-mechanical coupling simulation in in-situ oil shale mining

Shuang Liang[(a)], Yi Pan[(a)], Mingzhe Guo[(a)]*, Hui Yang[(b)]

(a) College of Oil and Gas Engineering, Liaoning Petrochemical University, Fushun 113001, China
(b) Kunlun Safety & Health Technology Company, Beijing 102200, China

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Abstract. *Against the backdrop of surging global energy demand, oil shale, as a plentiful unconventional energy resource, has emerged as a research hotspot for in-situ exploitation. Oil shale pyrolysis involves temperature, seepage, and stress field coupling, leading to surface deformation and fracture propagation that affect mining efficiency. Thermal-hydraulic-mechanical coupling simulation can effectively reveal multi-physical field interaction mechanisms in reservoirs and offer theoretical support for optimizing mining processes. This paper reviews its application in in-situ oil shale mining, summarizes coupling theories and mathematical models, and analyzes its value in heat injection mining, effective pyrolysis zone prediction, and ground surface deformation analysis. It also summarizes key applications and prospects for future directions, and provides theoretical and technical references for optimizing in-situ oil shale mining, thereby laying a foundation for subsequent thermal-hydraulic-mechanical-chemical research.*

Keywords: *oil shale, in-situ oil shale mining, thermal-hydraulic-mechanical (THM) coupling, thermal-hydraulic-mechanical (THM) coupling simulation, in-situ heat injection mining.*

1. Introduction

Currently, global energy demand continues to grow, while traditional petroleum resources are increasingly depleted due to long-term extraction. This supply–demand contradiction is accelerating the strategic transition in the energy sector, making the development of unconventional energy a key pathway to address the challenge. Among these, oil shale has attracted widespread attention owing to its significant advantages of extensive distribution and abundant reserves [1, 2]. As shown in Figure 1, the global proven reserves

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* Corresponding author, gmz_lsh@126.com

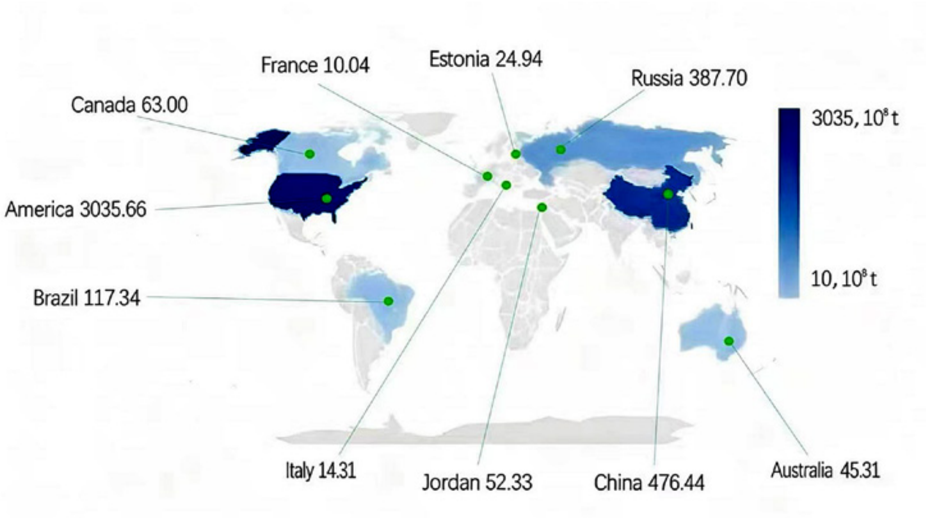


Fig. 1. Distribution map of proven oil shale reserves worldwide.

of oil shale can reach as high as 400 billion tons, demonstrating significant potential for industrial development and application [3]. Therefore, oil shale is regarded as one of the important alternative energy sources to conventional resources [4, 5]. In-situ mining technology promotes the pyrolysis of kerogen in oil shale to generate oil and gas through underground heating. Due to its advantages of reduced environmental impact and high resource utilization efficiency, it has become the main technical approach for the industrial development of oil shale [6, 7]. Oil shale pyrolysis is the process where kerogen decomposes into shale oil, gas, and water at high temperatures. This process triggers a series of physicochemical reactions such as water volatilization, kerogen thermal decomposition, and rock fracture, promoting the formation of pores and fractures and significantly enhancing permeability [8, 9]. These microscale pores and fractures serve as both channels for the migration of pyrolysis products and spaces for internal heat exchange, directly determining rock permeability and representing a crucial link for the efficient realization of in-situ conversion [10].

However, in-situ oil shale mining is a complicated, coupled process involving heat conduction, fluid seepage, rock deformation, and chemical reactions [11]. The high temperatures induced by heat injection not only drive the pyrolysis of organic matter but also lead to complex dynamic interactions among the reservoir temperature field, seepage field, and stress field. These interactions directly affect pyrolysis efficiency, the formation of fracture networks, and even formation stability [12]. Traditional single-physics field models or uncoupled models with simple superposition fail to effectively address rock thermal deformation, mechanical property evolution, pyrolysis product generation, seepage-induced pore pressure changes, and their fracturedriving effects, all of which result from temperature variations. Nor can they account for the reverse impact of stress field redistribution on pore structure and seepage–thermal conduction paths. This limits the reliability of process parameter optimization and safety assessment in in-situ oil shale exploitation.

Thermal-hydraulic-mechanical (THM) coupling simulation integrates temperature fields, rock deformation, and fluid seepage to reveal multi-physical field coupling behaviors during in-situ oil shale exploitation [13]. Notably, while pyrolysis is inherently a chemical process and current research has extended to thermal-hydraulic-mechanical-chemical (THMC) coupling simulation, this paper focuses on THM coupling simulation. It captures the core mechanisms governing pyrolysis: heat transfer, fluid migration, fracture propagation, and rock deformation. In practice, chemical processes such as kerogen conversion kinetics are often simplified as heat and fluid source terms, integrated into THM models to indirectly capture their effects. By concentrating on this central mechanism, the paper reviews the theoretical and application progress of THM simulation, discussing its value in heat injection mining, effective pyrolysis zone and fracture prediction, and ground surface deformation analysis. This work supports the optimization of oil shale extraction parameters and risk prevention, while laying a physical foundation and establishing a model framework for subsequent comprehensive studies on THMC multi-field coupling.

2. Theory and model of thermal-hydraulic-mechanical coupling simulation

As a crucial method for investigating the interactions among multi-physics fields during the in-situ mining of oil shale, THM coupling simulation has its theoretical basis and model construction directly determining the accuracy and reliability of the simulation.

2.1. Theoretical origin of THM coupling simulation

Fluid-solid coupling serves as the foundation of THM coupling. The earliest research on fluid-solid coupling originated with Terzaghi, who proposed the effective stress principle and one-dimensional consolidation theory, thereby laying the groundwork for subsequent studies. However, the initial theory was limited by its assumptions and had restricted capability in solving practical problems [14]. Subsequently, in 1955–1956, Biot [15, 16] built upon this work and established a more comprehensive three-dimensional consolidation model for isotropic porous media under isothermal conditions, later extending the consolidation theory to anisotropic porous media and dynamic analysis. Rice and Cleary [17] introduced the easily determinable Skempton constant, deriving an alternative expression of Biot's theory. In 1984, Zienkiewicz and Shiomi [18] further advanced the development of fluid-solid coupling theory by accounting for geometric and material nonlinearities, proposing a generalized form of Biot’s theory.

It is noteworthy that in the fluid-solid coupling theory, the temperature field remains constant. However, during the actual development of oil and gas reservoirs – especially for low-permeability reservoirs such as oil shale – the reservoir temperature undergoes significant changes during the dynamic mining process. Temperature variation not only directly affects the mechanical properties of rocks but also influences the fluid seepage process through changes in fluid physical property parameters. Meanwhile, rock deformation leads to alterations in pore structure, which in turn affects fluid seepage [13]. These factors interact with each other, forming a complex coupling effect among THM fields, as illustrated in Figure 2.

Therefore, traditional fluid-solid coupling models can no longer accurately simulate the real conditions of reservoirs. It is necessary to thoroughly consider the coupling effects among temperature variation, rock deformation, and fluid seepage, which has led the THM coupling theory to gradually become a research focus in the field of oil and gas reservoir development.

In early studies, Bear and Corapcioglu [19] investigated the variations in in-situ stress, temperature, and rock permeability within geothermal regions during geothermal resource extraction. Lewis et al. [20] accounted for the influence of temperature changes on fluid density, phase transitions, and rock thermal expansion, and analyzed how rock deformation alters fluid flow paths through changes in porosity and permeability. Additionally, they noted that variations in fluid pressure during seepage exert a feedback effect on the rock skeleton. Jing et al. [21] conducted research on fluid flow, solid deformation,

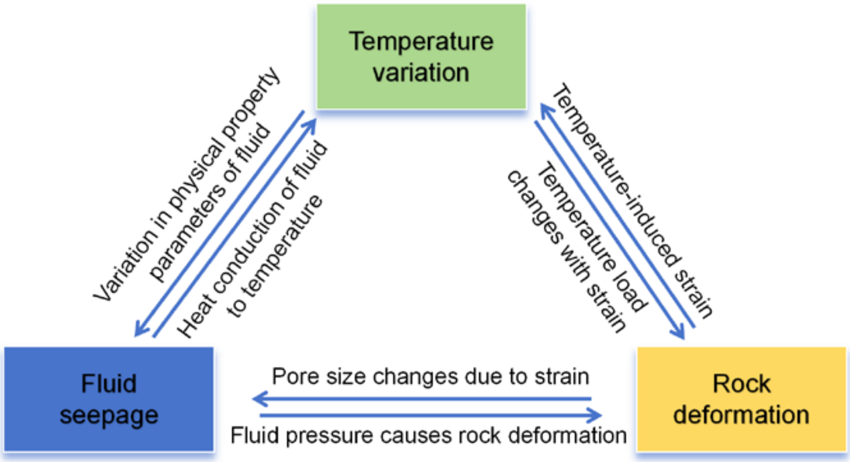


Fig. 2. Thermal-hydraulic-mechanical coupling diagram.

and heat transfer in hard rock structures but did not systematically consider the full coupling effect among temperature, seepage, and deformation. In 1997, Gutierrez and Makurat [22] developed a THM coupling model to investigate the fluid-solid coupling process during water injection into pressurized fractures; however, limited by technical constraints, the relationship between the temperature field and rock deformation was not considered. Starting from the interrelationships among rock mass seepage, stress, and temperature, Chai [23] established a coupling mechanism for THM processes.

With the deepening of research, scholars have progressively applied the THM coupling theory to the in-situ mining of oil shale. In 2008, Kang [24] was the first to integrate the theories of rock mechanics, heat transfer, and seepage mechanics, establishing a THM coupling mathematical model for the in-situ heat injection mining of oil shale. This model provided a crucial basis for the application of THM coupling simulation in oil shale-related studies. Zhao [25] further developed a THM coupling model for the underground co-gasification and thermal mining of oil shale and coal, analyzing the dynamic distribution laws of the temperature field, seepage field, and stress field during the gasification process of oil shale reservoirs. Wang [26] pioneered the establishment of an anisotropic THM coupling mathematical model for oil shale. Utilizing parameters related to heat transfer, seepage, mechanics, and deformation obtained from laboratory experiments, he analyzed the variation laws of reservoir pore pressure, temperature, stress, deformation, permeability, and production during the in-situ pyrolysis of oil shale. Jin et al. [27] developed a THM-coupled model that incorporates the temperature dependence of key properties of oil shale and the transverse isotropy resulting from its bedding structure. This model integrates multi-stage pyrolysis kinetics of kerogen, fluid flow in porous media, and heat transfer processes, providing theoretical guidance and parameter optimization strategies for the field application of in-situ oil shale conversion.

Amid in-depth research on in-situ oil shale conversion mechanisms and a growing understanding of multi-field coupling effects during extraction, the THM coupling theory has expanded toward two key directions: one focuses on developing a fully coupled THMC model, which integrates chemical reaction kinetics (e.g., kerogen pyrolysis) into the physical field coupling system to accurately simulate the interactions among heat transfer, product generation, and rock mass deformation [28, 29]; the other centers on developing a refined model considering anisotropy, which couples thermal damage theory with anisotropic constitutive relations to characterize the evolution of permeability and mechanical properties induced by directional fracture development [30, 31]. These advancements have propelled simulations from traditional three-field physical coupling to a new stage of full physical-chemical coupling and dynamic characterization of reservoir properties, providing more precise theoretical support for optimizing in-situ mining processes.

2.2. Construction of the mathematical model of THM coupling simulation

The mathematical model of THM coupling forms the core of numerical simulation and can be broadly categorized into non-complete coupled and complete coupled approaches [32]. Non-complete coupled models introduce temperature-related functions based on fluid-solid coupling frameworks but fail to account for the dynamic coupling effects among temperature variations, rock deformation, and fluid flow. For instance, Wang et al. [33] developed a non-complete coupled mathematical model that comprises the following three types of equations: seepage equations, rock deformation equations, and thermal strain equations.

Seepage equation:

$$\nabla\left[\frac{KK_r\rho}{\mu}\nabla(p-\gamma D)\right]-\nabla(\phi S\rho v_s)+q=\frac{\partial(\phi S\rho)}{\partial t}, \tag{1}$$

where ∇ is the Hamilton operator, K is the absolute permeability of oil and gas reservoirs (mD), D is elevation (m), Kr is the relative permeability of oil and gas reservoirs (mD), μ is fluid viscosity (mPa · s), γ is the weight rate, ρ is density (g/cm^3), p is fluid pressure (MPa), ϕ is porosity, v_s is the absolute velocity of solid particles (cm/s), S is fluid saturation, t is time (s), and q is the source or sink of material change per unit volume (cm^3/s).

Rock deformation:

$$\sigma'_{ij,i}+\left(p\delta_{ij}\right)_i+\sigma^h_{ij,i}+[(1-\phi)\rho_s+\phi S_o\rho_o+\phi S_w\rho_w]g_j=0, \tag{2}$$

$$\varepsilon_{ij}=\frac{1}{2}\left(u_{i,j}+u_{j,i}\right), \tag{3}$$

$$d\sigma'_{ij}=D^{ep}d\varepsilon_{ij}, \tag{4}$$

where $\sigma'_{ij,i}$ is the effective stress tensor (MPa), $\sigma^h_{ij,i}$ is thermal stress (MPa), δ_{ij} is the Kronecker function, ε_{ij} is the strain tensor, u is displacement (m), D^{ep} is an elastic-plastic matrix, g_j = [0 0 g], where g is the acceleration of gravity (m/s^2), S_o and S_w are oil saturation and water saturation, respectively, ρ_o and ρ_w are the density of oil and water, respectively (g/cm^3), and ρ_s is rock skeleton density (g/cm^3).

Thermal strain equation:

$$\{R\}^e+\iiint[B]^T[D][\varepsilon_0]dx\,dy\,dz=[K]^e\{\delta\}^e, \tag{5}$$

where $\{R\}^e$ is the equivalent nodal force due to external forces, $[B]^T$ is the element strain matrix, $[D]$ is the constitutive matrix for the unit, $[\varepsilon_O]$ is the unit thermal strain, $[K]^e$ is the element stiffness matrix, and $\{\delta\}^e$ is the virtual displacement of the node.

In contrast, complete coupled models comprehensively account for the coupling effects among temperature variation, rock deformation, and fluid seepage, making them more consistent with the actual conditions of temperature-varying oil and gas reservoirs. The fully coupled mathematical model constructed by Li et al. [34] comprises three components: seepage equations, temperature field equations, and rock deformation equations. Within the seepage equations, the influences of temperature and pressure on fluid density, viscosity, and rock permeability are comprehensively considered, the temperature field equations incorporate the effect of solid deformation on heat energy conservation, and the rock deformation equations take into account the roles of fluid pore pressure and thermal stress. This model system can describe the physical phenomena in the oil shale mining process more accurately and provide a more reliable basis for numerical simulations.

Seepage equation:

$$\nabla\left[\frac{K}{\mu_f}\nabla\left(p+\rho_f g z\right)\right]+c_a\frac{\partial T}{\partial t}-c_k\frac{\partial p}{\partial t}-(1-\phi)\frac{\partial \varepsilon_k}{\partial t}=0, \tag{6}$$

where ρ_f is fluid density (g/cm^3), μ_f is fluid viscosity (mPa · s), c_a is the average coefficient of thermal expansion, c_k is the average volume compression coefficient, ε_k is volume strain, z is depth (m), and T is the absolute temperature change value at a certain point in the rock mass (K).

Thermal strain equations:

$$c\frac{\partial T}{\partial t}+\rho_f c_f\left(v_f\nabla\right)T+\beta T_0\frac{\partial \varepsilon_k}{\partial t}-c_t T_0\frac{\partial p}{\partial t}-\nabla(\lambda\nabla T)=0, \tag{7}$$

$$c_t=\frac{(1-\phi)\rho_s c_s}{k_s}+\frac{\phi\rho_f c_f}{k_f}, \tag{8}$$

where T_0 is the absolute temperature (K), c is the average heat capacity, c_s and c_f are the heat capacity coefficients of the solid and fluid, respectively, β is the thermal stress coefficient, k_s and k_f are the bulk elastic moduli of the solid and fluid, respectively (MPa), λ is the average thermal conductivity, and v_f is the seepage velocity (cm/s).

Rock deformation equations:

$$\left.\begin{aligned}
(G+\gamma)\frac{\partial \varepsilon_k}{\partial x}+G\nabla^2 u+\alpha\frac{\partial p}{\partial x}-\beta\frac{\partial T}{\partial x}+f_x&=\rho_s\frac{\partial^2 u}{\partial t^2}\\
(G+\gamma)\frac{\partial \varepsilon_k}{\partial y}+G\nabla^2 v+\alpha\frac{\partial p}{\partial y}-\beta\frac{\partial T}{\partial y}+f_y&=\rho_s\frac{\partial^2 v}{\partial t^2}\\
(G+\gamma)\frac{\partial \varepsilon_k}{\partial z}+G\nabla^2 w+\alpha\frac{\partial p}{\partial z}-\beta\frac{\partial T}{\partial z}+f_z&=\rho_s\frac{\partial^2 w}{\partial t^2}
\end{aligned}\right\}, \tag{9}$$

where G and γ are the Lamé coefficients, α is the Biot coefficient, f_x, f_y, and f_z are the volume force components, and u, v, and w are the solid displacement components.

The mathematical model for THM coupling simulation is a complex interdisciplinary system involving multiple fields such as thermodynamics, fluid mechanics, solid mechanics, and chemical reactions. By coupling these physical processes, the physical and chemical behavior of oil shale during the in-situ mining process can be simulated and predicted more accurately.

3. Application of thermal-hydraulic-mechanical coupling simulation of oil shale

THM coupling simulation holds broad application prospects in oil shale development, with its specific applications in areas such as in-situ heat injection mining, effective pyrolysis zone prediction, and ground surface deformation analysis significantly advancing the understanding and optimization of in-situ mining processes.

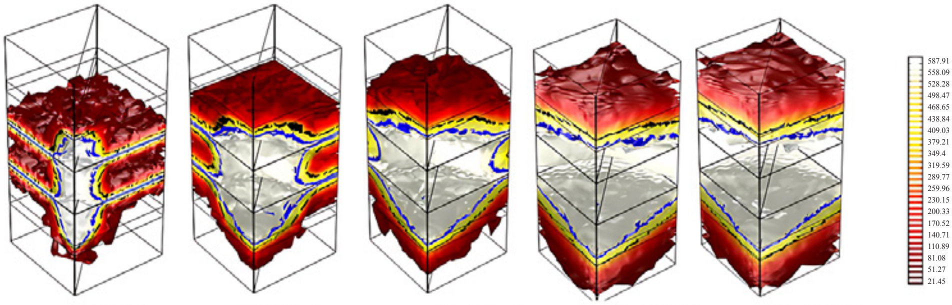
3.1. Simulation and optimization of in-situ heat injection mining

In the in-situ thermal injection mining of oil shale, high-temperature steam is injected into the oil shale reservoir to heat and decompose the organic matter stored therein into oil and gas products. Meanwhile, the mineral skeleton of oil shale undergoes complex physicochemical changes, forming seepage channels conducive to product transportation. This process involves intricate THM coupling effects [35].

THM coupling simulation can reveal the interrelationships among steam migration, temperature propagation, and rock deformation. For instance, Kang [24] established a THM coupling mathematical model for in-situ steam injection development of oil shale, which represents a crucial breakthrough in the application of THM coupling simulation technology in the field of in-situ heat injection mining of oil shale.

Liu [36] further studied the evolution of the physical properties of oil shale and fluids under the action of temperature and pressure. Through THM coupling simulation, he analyzed the dynamic distribution laws of the temperature field, seepage field, and displacement field during the in-situ heat injection process of oil shale, providing a reference basis for the in-situ heat injection mining of oil shale.

Wang et al. [37] took the Fushun oil shale reservoir as the research object, set the injection temperature at 650 °C and the injection pressure at 3 MPa, and compared the efficiency of conduction heating and steam convection heating by THM coupling simulation. Under the same pyrolysis time, the effective pyrolysis area ratio of steam convection heating is 22.4 times that of conduction heating, and the oil production is 7259 times that of conduction heating, which fully proves that the efficiency of convection heating pyrolysis of oil shale is much higher than that of conduction heating.



(a) 30 d (b) 150 d (c) 300 d (d) 500 d (e) 800 d

Fig. 3. Temperature distribution of the reservoir at different times [38].

To accurately simulate the in-situ pyrolysis process of oil shale, Wang et al. [38] established a coupled model considering transversely isotropic THM characteristics to simulate the in-situ pyrolysis process of superheated steam. Figure 3 shows the temperature distribution of in-situ steam injection pyrolysis of oil shale at different times. The temperature of the ore layer within the blue line is higher than 550 °C, and the temperature of the ore layer outside the black line is lower than 350 °C. It can be seen from the figure that the initial heat is transmitted along high-permeability fractures. Because the permeability of the parallel bedding is much higher than that of the vertical direction, and the high pressure of the wellbore promotes the migration of steam, an ellipsoidal high temperature zone is rapidly formed. At 500 days, the oil shale between the injection and production wells basically reaches the pyrolysis temperature. THM simulation can intuitively show the dynamic evolution law of reservoir temperature field with steam injection time, and provide key visual evidence for understanding the oil shale pyrolysis process.

In 2025, Chen et al. [30] pioneered the integration of a statistical damage variable into the THM coupling theory for three-dimensional fractured rock masses. They developed a coupled model that incorporates anisotropic thermal damage and a transverse isotropic constitutive law. Using COMSOL simulations of the in-situ conversion process under convective heating, their study revealed the intrinsic relationship between the anisotropy of pore structures and the physico-mechanical properties of oil shale during in-situ steam injection pyrolysis.

3.2. Prediction of effective pyrolysis zone and fracture propagation

The dynamic evolution of the effective pyrolysis zone and the law of fracture propagation are the core factors that determine the mining efficiency of oil shale. THM coupling simulation provides key technical support for improving reservoir utilization efficiency and optimizing mining conditions by accurately quantifying the influence of the temperature field on kerogen pyrolysis and the development mechanism of fractures under the coupling of the three fields.

THM coupling simulation can accurately predict the variation law of the effective pyrolysis zone of the reservoir and its pyrolysis effect, and this evolution has become a key indicator for evaluating mining efficiency in in-situ oil shale heat injection exploitation. The objective of in-situ oil shale exploitation is to fully pyrolyze its organic matter (kerogen). Consistent with existing findings, Wang et al. [39] and Saif et al. [40, 41] demonstrated that the complete pyrolysis temperature of oil shale kerogen is generally above 400 °C. Only when the temperature threshold is reached can kerogen undergo sufficient pyrolysis, generating recoverable oil and gas products. Thus, to define the temperature range enabling sufficient kerogen pyrolysis and meeting exploitation needs, 400 °C is designated as the effective pyrolysis temperature, and the zone with temperatures above 400 °C is defined as the effective pyrolysis zone.

Tang et al. [42] revealed the multi-physical field variation law of the reservoir during in-situ heat injection mining of oil shale using THM coupling simulation and conducted an in-depth analysis of the variation law of the effective pyrolysis zone of the Fushun oil shale reservoir with heat injection time, which provided an important theoretical reference for the in-situ heat injection mining of oil shale.

Addressing the challenges of unclear evolution patterns in the reservoir's effective pyrolysis zone and difficulties in accurately evaluating actual pyrolysis effectiveness during in-situ heat injection mining of oil shale, Yu et al. [43] developed a THM coupling model that incorporates two distinct types of random fractures: bedding fractures and hydraulic fractures. Through THM coupling simulation, they successfully analyzed the evolution characteristics of the effective pyrolysis zone during the in-situ thermal extraction process. As shown in Figure 4a, when superheated steam diffuses along bedding fractures, multiple narrow and elongated primary pyrolysis pathways are formed. In contrast, Figure 4b demonstrates that when superheated steam propagates through hydraulic fractures, it does not form such elongated pathways but rapidly establishes a dendritic high-temperature network.

In addition, the stress field distribution of the oil shale reservoir and its influence on fracture propagation are also a research focus of THM coupling simulation. The fracture propagation of oil shale is not only affected by the temperature field during pyrolysis but also by the combined action of the in-situ stress field and fluid pressure. Based on the THM coupling model, Huang [44] found that fractures exhibit bidirectional propagation characteristics under the combined effects of thermal stress and expansion forces: outward extension when dominated by expansion forces, and inward propagation when primarily driven by thermal stress. Moreover, thermal stress plays a critical role in determining the initiation locations and quantity of fractures.

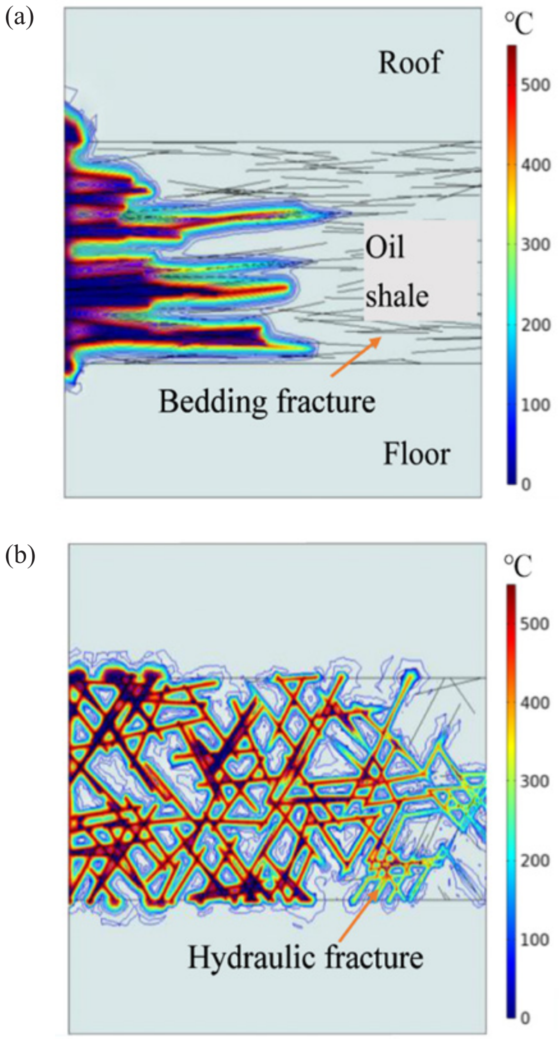
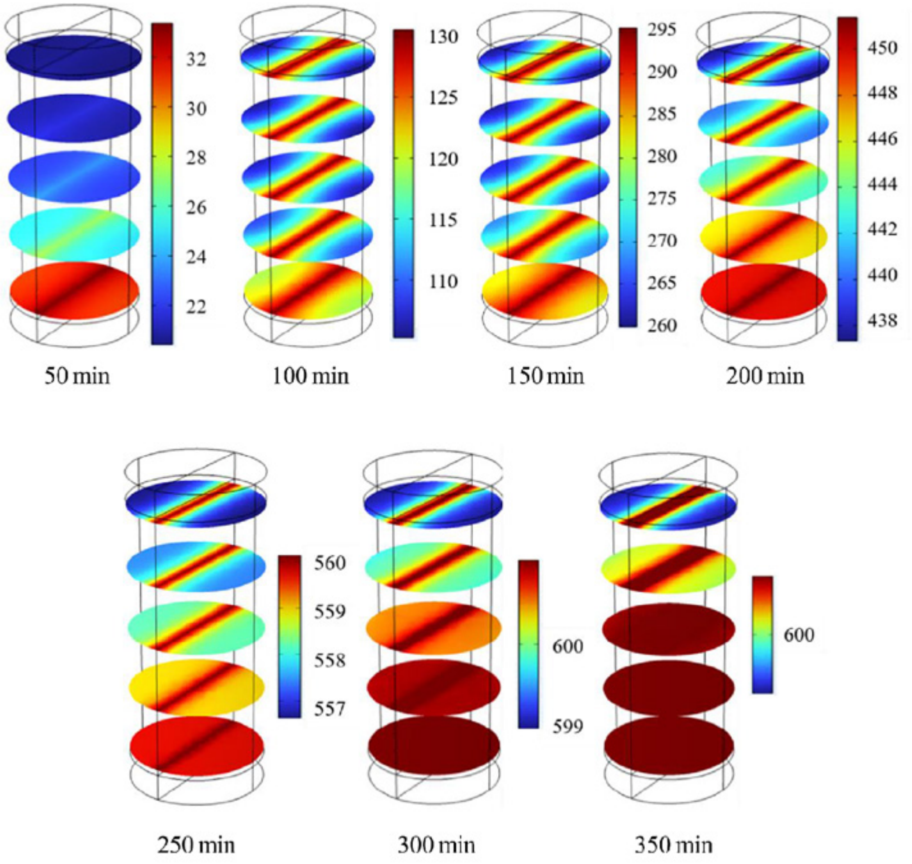


Fig. 4. Temperature changes in a bedding fracture reservoir (a) and in a hydraulic fracturing reservoir (b) with heat injection time [43].

On this basis, Lee et al. [45, 46] used a self-developed kerogen pyrolysis simulator with complete functions to simulate the kerogen pyrolysis process in a steam-injected multi-stage horizontal well system with transverse fractures. They clarified that the fluid conduction effect of fractures and the irreducible water saturation of the reservoir matrix jointly influence oil production capacity.

In 2024, Jia et al. [47] further constructed Case 1 (single fracture, hydraulic fracturing) and Case 2 (multi-fracture, hydraulic fracturing + penetrating thermal fracturing) models and used THM coupling simulation technology to simulate the heat transfer process under 200 m buried depth stress. The temperature distribution cloud diagram is shown in Figure 5. The single-crack model presents a “single-peak” heat transfer mode. The heat is mainly concentrated around the crack, and the temperature at the center of the crack is the highest. In contrast, the multi-crack model presents a “multi-peak” heat transfer mode, and the high-temperature region covers a wider range. At the same time, they also studied the effects of permeability and external stress on oil shale pyrolysis. It is found that under the condition of constant external stress and thermo-mechanical coupling, after exceeding the critical temperature of oil shale, the mechanical strength of the rock increases significantly, and the permeability increases sharply.

(a)



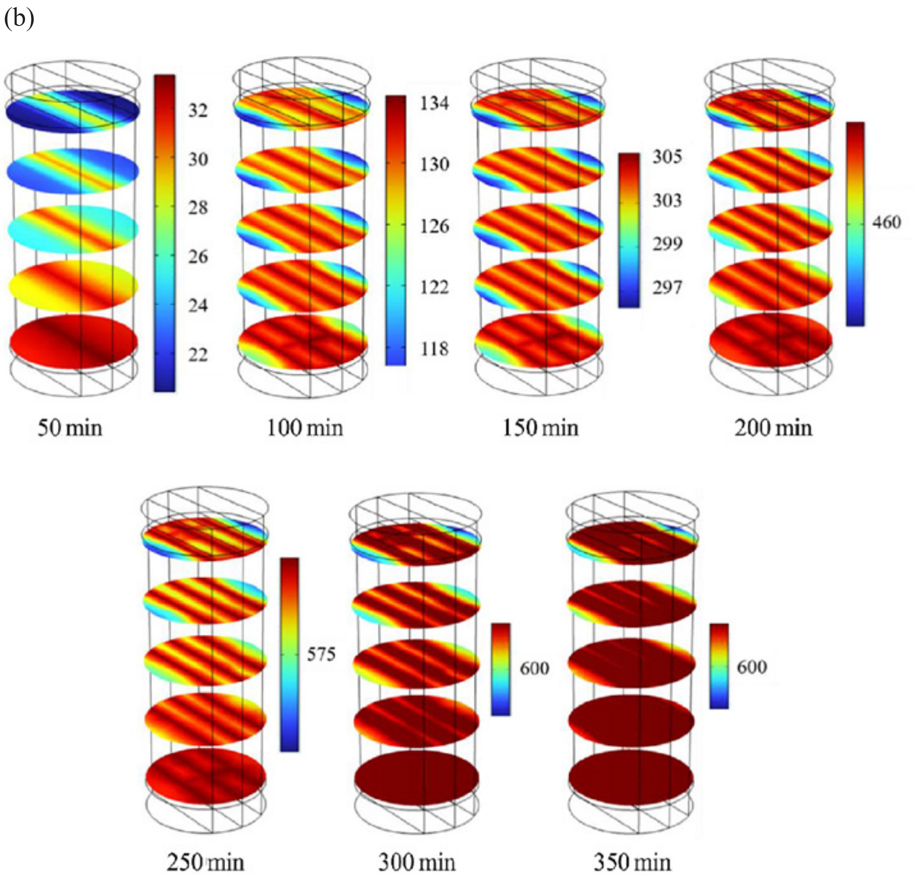


Fig. 5. Cloud diagram of the heat transfer process in Case 1 (a) and Case 2 (b) [47].

3.3. Dynamic mechanism of ground surface deformation

In the process of in-situ oil shale mining, ground surface deformation and ground subsidence not only affect the normal operation of downhole equipment but may also trigger environmental and geological problems [48]. By integrating the mechanical properties of rock masses and multi-field coupling effects, THM coupling simulation can quantify the laws of ground surface deformation and reveal the intrinsic mechanism of deformation, which provides core support for engineering risk prevention and control and the formulation of environmentally friendly mining schemes.

Zhao et al. [49] combined THM coupling simulation with practical engineering requirements. Through simulation, it was found that during horizontal well production, the fluid short-circuited along high-permeability channels, resulting in low heating efficiency in the early stage, and the uneven heating further increased the difference in bottom-hole deformation. In addition, they quantitatively analyzed the dynamic characteristics of surface deformation, providing a reference for the design of the in-situ oil shale mining process and the formulation of equipment protection schemes.

Aiming at environmental geological problems such as ground subsidence after in-situ mining of oil shale, Zhang et al. [50] innovatively combined physical experiments, theoretical analysis, and THM coupling simulation to construct a transverse anisotropy constitutive model suitable for in-situ mining deformation of oil shale, and revealed the internal mechanism of oil shale deformation under thermal action. The results show that the reservoir reaches the target temperature within 16 days, and the vertical final deformation is about 6.5 cm. The influence of in-situ mining on the geological environment is less than that of the traditional method, which provides a practical paradigm for this kind of coupling simulation in the study of heterogeneous rock mining.

Hu [51] studied ground surface deformation throughout the entire process of in-situ oil shale mining. Based on the convective heating method, FLAC3D software was used to construct the whole stratum numerical model of the Fuyu in-situ oil shale mining pilot test base. The whole process of in-situ oil shale mining was simulated using THM coupling. It was revealed that the thermal expansion and stress concentration of the rock mass near the heating well were caused by rapid heat flow in the heating stage, which promoted the surface uplift of 2.93 cm. In the cooling stage, the stress concentration of the rock mass was weakened after cooling, and the compression of the oil shale led to surface settlement of 3.52 cm.

In 2024, Song et al. [52] constructed a THM coupling model considering the dynamic changes in pore structure and in thermophysical and mechanical parameters with temperature to analyze the multi-field evolution and ground surface deformation caused by in-situ mining of oil shale. The results show that surface displacement exhibits the evolution characteristics of heating-induced uplift, cooling-induced subsidence, and steady-state stabilization, and the final stratum settlement is about 0.59 cm.

In summary, the application of THM coupling simulation in in-situ mining of oil shale has important theoretical and practical significance. Through comprehensive analysis of the interaction among the temperature field, fluid field, and stress field, THM coupling simulation clarifies the mechanism of efficient steam injection pyrolysis, accurately predicts the evolution law of the pyrolysis zone under different fracture systems, as well as quantitatively reveals the formation deformation caused by in-situ oil shale mining, providing critical theoretical support and a decision-making basis for the implementation of efficient, safe, and environmentally friendly in-situ mining of oil shale. The application of THM coupling simulation is summarized in this paper, as shown in Table 1. Currently, with advances in model refinement, full multi-field coupling, and multi-scale characterization technologies, THM coupling simulation is gradually expanding to full THMC simulation to more comprehensively depict the interaction mechanisms between chemical processes such as pyrolysis kinetics, product generation, and migration and physical fields. This has further enhanced the predictability and controllability of oil shale exploitation under complex geological conditions, advancing oil shale resource development toward a safer, more efficient, and environmentally friendly model.

Table 1. Summary of applications of THM coupling simulation in oil shale

Direction of application	Core objective	Main conclusion
Simulation and optimization of in-situ heat injection mining	Accurate simulation of the oil shale pyrolysis process and improvement of pyrolysis efficiency	Steam pyrolysis efficiency is higher than that of conduction heating, and the intrinsic correlation between anisotropy and the pore-mechanical properties of oil shale should be considered
Prediction of effective pyrolysis zone and fracture propagation	Expanding the pyrolysis range and shortening the mining cycle	Hydraulic fractures are more efficient than bedding fractures, and multi-fracture networks achieve wide-area high-temperature coverage
Dynamic mechanism of ground surface deformation	Preventing geological risks and ensuring equipment safety	Ground surface deformation is characterized by “heating uplift–cooling subsidence–steady state”

4. Conclusions

THM coupling simulation quantifies the coupling effects of temperature, seepage, and stress fields, revealing the core mechanisms of in-situ oil shale exploitation. It delivers key theoretical support for optimizing mining parameters, risk mitigation, and engineering design, with its application value fully demonstrated in heat injection efficiency improvement, effective pyrolysis zone prediction, and ground surface deformation analysis.

1. Oil shale pyrolysis efficiency depends on the synergy of temperature transfer, fracture development, and fluid migration: the temperature field initiates pyrolysis, the stress field controls fracture propagation, the seepage field affects heat and product transport, and their dynamic balance is key to efficient exploitation.
2. Accurate prediction of the effective pyrolysis zone requires centering on the 400 °C pyrolysis temperature threshold and integrating fracture morphological characteristics. Hydraulic fractures can significantly shorten the pyrolysis cycle compared with parallel bedding fractures,

while multi-fracture networks enable broader high-temperature coverage than single fractures.

3. The dynamic evolution of surface deformation can be predicted in advance via coupling simulation, exhibiting the intrinsic characteristics of heating-induced uplift, cooling-induced subsidence, and steady-state stabilization. Moreover, in-situ mining causes less disturbance to the geological environment than traditional mining technologies.

Currently, THM coupling simulation still has limitations. First, the full THMC coupling mechanism is not fully clarified, with insufficient deep integration of chemical processes and physical fields. Second, simulation parameters lack adequate matching with field operating conditions, compromising the accuracy of engineering guidance.

Future research should prioritize developing THMC models and strengthening the coupling of multi-scale reservoir heterogeneity with pyrolysis kinetics. Meanwhile, a multi-scale parameter inversion method should be established by integrating micro-CT and field monitoring data to enhance model adaptability to real reservoirs, providing comprehensive technical support for maximum oil shale resource utilization and precise mining risk control.

Data availability statement

No new data were generated or analyzed in support of this review.

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