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A review on oil shale in-situ mining technologies: Opportunities and challenges

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Abstract. *The principle and application of oil shale in-situ mining technology are reviewed. Oil shale is rich in resources and is an important supplement to petroleum and natural gas as a source of energy. Currently, ground retorting technology is the primary way to produce shale oil because of its elaborated processing method and equipment. However, this technology has several disadvantages such as low thermal efficiency, high environmental pollution and inability to exploit deeply buried oil shale. A novel method called oil shale in-situ mining technology is efficient and environmentally friendly. This technology can exploit deep oil shale while reducing pollution and greenhouse effect. Based on the data collected, this paper summarizes the development of global underground in-situ oil shale mining technology, introduces four heating transfer principles and mathematical models of conduction heating, convection heating, radiation heating and combustion heating, clarifies the process flow, as well as presents advantages and disadvantages of different technologies. It provides a reference for the research of oil shale in-situ mining technology, and also looks into the technology's prospects for industrialization, integrating with greenization, information and intelligence.*

Keywords: *oil shale in-situ mining, conversion technology, heating methods, heating transfer principle.*

1. Introduction

Based on the data of the Energy Information Administration (EIA) and Advanced Resources International (ARI), the global total shale oil geological resources were 936.835 billion tons, and the technically recoverable resource was 61.847 billion tons until 2017 [1]. The development of oil shale becomes one of the effective ways to alleviate oil and gas supply and demand pressure in the world.

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Oil shale is a high-ash sedimentary rock containing combustible organic matter. Its oil content is over 3.5%. The calorific value of sapropel- and mixed-type oil shale is higher than 4.18 MJ/kg [2]. The organic matter in oil shale undergoes chemical decomposition at 350–550 °C to produce oil and gas. The industrial utilization of oil shale began in France in 1838, having thus a 200-year history. The industry declined with the outbreak of World War II, the energy crisis and the rising petroleum profession. The low oil price period has ended because of political, economic, and resource shortage reasons in the 21st century. The oil price has risen to 70–80 USD/bbl, or even to 145.31 USD/bbl in the world. At the same time, the production cost in some countries, such as Estonia, Brazil and China, is about 30–40 USD/bbl. Sufficient economic benefits provide a good prospect for the development of oil shale industry [3].

Currently, the aboveground retorting technology is used to explore oil shale resources. Although the said technology has been quite well developed, there occur concerns such as low utilization rate, increased pollution, high cost, large land occupation and recycling problems [4]. Given the above and the characteristics of global oil shale resource burial and distribution, the oil shale in-situ mining technology involves green environmental protection, low development cost and small floor area. Today, an international frontier technology is used in the deep oil shale exploration. This technology plays an important role in alleviating global energy shortages, reducing land pressure and improving the environment. However, it has not yet industrially developed due to some technical problems which need to be solved.

Four global in-situ mining technologies have been pointed out. The technical principles, process flow and characteristics of related technologies have been briefly introduced. The advantages and disadvantages of each technology have been highlighted. Based on relevant information, the future of each technology has been analyzed and suggestions for the development globally put forward.

2. Current technology

Oil shale in-situ mining consists in underground retorting. By heating the oil shale reservoir at high temperature, pyrolysis of solid kerogen to liquid hydrocarbon takes place, and then the extraction of the liquid hydrocarbon from the underground through the traditional oil and gas drilling and production process occurs [5]. High-temperature pyrolysis of oil shale means the heat transfer process in the rock. The study of heat transfer underlies the basis for exploring the principle of oil shale in-situ mining technology.

There are three heat transfer ways: heat conduction, heat convection and heat radiation [6, 7].

Heat transfer is a comprehensive process that involves heat conduction, heat convection and heat radiation. Different heat transfer modes follow various mechanisms. To more thoroughly explore the impact of heat transfer modes on oil shale in-situ mining, a single heat transfer mode was probed. Three methods of heating oil shale reservoirs, namely, heat conduction, heat convection and heat radiation, have been developed on this basis.

Sinclair Oil and Gas Company conducted an experiment on oil shale underground retorting in 1953. This technology consists in injecting high-pressure air into the ground through thermal injection wells and burning oil shale [8]. This is different from traditional physical heating, which is the chemical combustion reaction to heat. This creates a new method called combustion heating for oil shale in-situ mining, which uses the heat released by chemical combustion as the heat source.

This paper studies the current oil shale in-situ mining technology by using different modes of heating oil shale reservoirs: conductive heating, convection heating, radiation heating and combustion heating [9]. Table 1 lists the four methods of heating oil shale and overviews the current research status.

Table 1. Classification and current situation of oil shale in-situ mining technology

Heating mode	Process	R&D unit or company	Last status	References
Conduction	ICP	Shell	Demonstration	[10–12]
	ElectrofracTM	ExxonMobil	Pilot plan	[13, 14]
	GFC	IEP	Lab	[13, 14]
	HVF	Jilin University	Lab	[15]
Convection	CRUSH	Chevron	Abandon	[16]
	CCR	American Shale Oil	Abandon	[17, 18]
	IIST-VTPC	AsiaA.D.C.	Lab	[19]
	Superheated air	PetroProbe	Lab	[13, 14]
	IVE	Mountain West Energy	Pilot	[19]
	MTI	Taiyuan University of Technology	Pilot plan	[20]
	SCW	Jilin University	Lab	[15]
Radiation	Radio wave	Lawrence Livermore	Lab	[21]
	RF/CF	Schlumberger	Lab	[22]
	EOR	IITRI	Lab	[23]
	Microwave	Phoenix Wyoming, Inc.	Pilot plan	[23]
Combustion	In-situ combustion	U.S. Bureau of Mines	Pilot	[24]
	TIS	LETC	Lab	[25, 26]
	MIS	LLNL	Lab	[25, 26]
	TSA	Jilin University	Pilot	[27]

In-situ mining is applicable to oil shale resources with a buried depth of 300–1500 m. Oil shale is warmed by heating the well to bring about pyrolysis underground, the generated oil and gas are recovered through the production well. Jointly researched by the Exploration and Development Research Institute of the China National Petroleum Corporation (CNPC) and Shell, this technology enables carrying out the in-situ mining of oil shale 3000 m underground [28]. Compared with underground retorting, the said technology has several advantages: no open pit and mine mining, less oil shale waste accumulation, fewer by-products, low water consumption and minimal environmental pollution.

Based on China's previous oil shale research results and development achievements, the favorable and complete conditions for oil shale in-situ mining are summarized in [29–35], as given in Table 2.

Table 2. In-situ exploitation conditions of oil shale

Mining conditions	Specific indicators
Burial depth	300–1500 m (some technologies can reach 3000 m)
Pressure	It should be less than the overburden pressure
Temperature	340–500 °C; the heating time is 2–3 years, and, the longer the heating time, the more complete the conversion
Fissures	Fissures dip angle and fissures will affect the heat transfer during formation heating
Water mass fraction	5–20%
Ro, %	0.5–1.0
TOC, %	> 6
Layer thickness	> 15 m

Note: Excessive pressure exerted by mining can damage the formation.

The change of the water mass fraction will alter the reaction mode. Kerogen can undergo high-temperature cracking and aquathermolysis, which can reduce the proportion of heavy oil. Oil and gas are generated when the oil shale temperature is 350–550 °C, and the yield is the highest between 420 and 440 °C [36].

2.1. Conductive heating technology

Conduction is the heat transfer within an object or between two objects in contact. To transfer heat from one object to another, they must break contact and the conduction ends [37]. This transmission can take place between different parts of different objects or itself. Heat transfer occurs from high-temperature substances to adjacent low-temperature substances [38].

It is demonstrated that heat conduction happens on a particular substance Z in space. The function $u(t,x,y,z)$ is used to express the temperature at the coordinates (x,y,z) at time t on substance Z.

Heat transfer follows a general Fourier experimental law. In case of the infinitesimal dt time of a substance, the heat dQ flowing through an infinitesimal area dS along the normal direction n is proportional to the derivative $\frac{\partial u}{\partial n}$ of the substance temperature along the normal direction of the curve dS, as given by:

$$dQ = -k\left(x,y,z\right)\frac{\partial u}{\partial n}dSdt, \tag{1}$$

where $k(t,x,y,z)$ is the thermal conductivity coefficient of the substance at the coordinates (x,y,z), and the sign is positive. The negative sign in front of $-k\left(x,y,z\right)\frac{\partial u}{\partial n}dSdt$ in Equation (1) can be interpreted as the heat that is always flowing from the high-temperature area to the low-temperature area. Therefore, dQ and $\frac{\partial u}{\partial n}$ have different signs.

Taking any closed surface in matter D, φ represents the region of the surface derived from Equation (1), and between t_1 and t_2 all the heat through the surface φ can be expressed as:

$$Q = \int_{t_1}^{t_2}\left\{\iint_{\varphi} k\left(x,y,z\right)\frac{\partial u}{\partial n}dS\right\}dt, \tag{2}$$

where $\frac{\partial u}{\partial n}$ represents the directional derivative of u in the unit outer normal of the direction n on φ.

The incoming heat causes a change in the internal temperature of the medium. During the time interval $(t_1,\ t_2)$, the temperature of the medium changes from $u(t_1, x, y, z)$ to $u(t_2, x, y, z)$, and the heat it should absorb is:

$$\iiint_{\Omega} v\left(x,y,z\right)\rho\left(x,y,z\right)\left[u\left(t_2,x,y,z\right)-u\left(t_1,x,y,z\right)\right]dxdydz, \tag{3}$$

where v is the specific heat of the medium, ρ is the density.

Therefore, the following equation is established:

$$\begin{aligned}&\int_{t_1}^{t_2}\iiint_{\Omega}\left[\frac{\partial}{\partial x}\left(k\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial u}{\partial z}\right)\right]dxdydz\\ &=\iiint_{\Omega} v\rho\left(\int_{t_1}^{t_2}\frac{\partial u}{\partial t}dt\right)dxdydz\end{aligned}. \tag{4}$$

It is assumed that function u has a second-order continuous partial derivative with respect to variable x, y, z, and a first-order continuous partial derivative with respect to t. Using Green's Formula, Equation (4) can be written as follows:

$$\begin{aligned}&\int_{t_1}^{t_2}\iiint_{\Omega}\left[\frac{\partial}{\partial x}\left(k\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial u}{\partial z}\right)\right]dxdydz \\ &= \int_{t_1}^{t_2}\iiint_{\Omega} v\rho\frac{\partial u}{\partial t}dxdydz\end{aligned} \quad . \tag{5}$$

Thereafter exchange the integral order to obtain:

$$\int_{t_1}^{t_2}\iiint_{\Omega}\left[v\rho\frac{\partial u}{\partial t}-\frac{\partial}{\partial x}\left(k\frac{\partial u}{\partial x}\right)-\frac{\partial}{\partial y}\left(k\frac{\partial u}{\partial y}\right)-\frac{\partial}{\partial z}\left(k\frac{\partial u}{\partial z}\right)\right]dxdydz=0. \tag{6}$$

Since t_1, t_2, and region Ω are arbitrary, after transformation Equation (6) can be written as:

$$v\rho\frac{\partial u}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial u}{\partial z}\right). \tag{7}$$

Equation (7) is the heat conduction equation of heterogeneous isotropic substances.

Conductive heating technology is used to arrange heating elements or units in the oil shale reservoir. Its conduction medium is rock, which diffuses heat to the whole reservoir, accelerates kerogen natural maturity and makes it pyrolyze into oil and natural gas [39]. This technology has defects such as slow heating, low rate and high loss. The ripe conductive heating technologies are the Electrofrac™ technology of ExxonMobil, the geothermic fuel cell (GFC) technology of Independent Energy Partners (IEP) and the in-situ conversion process (ICP) technology of Shell.

ExxonMobil has been involved in oil shale development projects since the 1960s. After 30 years of development, the company proposed the Electrofrac™ process by investigating more than 30 processes at the end of the 20th century. It fills the large-scale fracture network formed by hydraulic fracturing with conductive proppant to create a heating unit to warm oil shale reservoirs [13, 14], as shown in Figure 1. The process has several positives. Compared with linear heat sources, this process heating unit has a larger surface area and can transfer sufficient temperature to the reservoir with fewer heating units. It has a planar shape, which can reduce interference in the ground environment that has different linear heat sources and downhole heaters. It can develop dense oil shale resources. The shortcomings of this heating unit include the following. Conductive proppants are needed to maintain conductivity at high temperatures. Special completion processes require efficient heat conduction. Lack of groundwater protection may easily cause water pollution. Ground heating equipment that has been operating in a high-temperature environment is prone to malfunctions, resulting in increased maintenance costs.

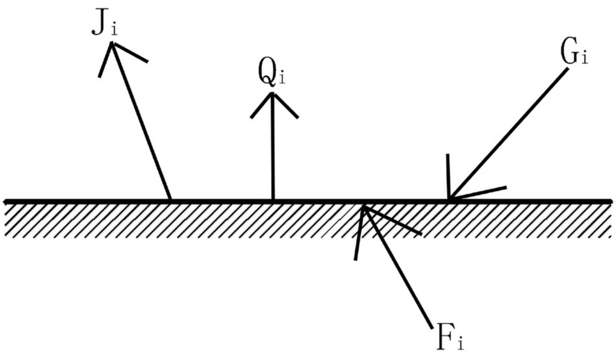

Fig. 1. Electrofrac™ technology of ExxonMobil.

IEP has a widely patented technology in oil shale mining – GFC. During the process, oil shale reservoirs are heated by using a high-temperature fuel cell stack that can burn natural gas [13, 14], as shown in Figure 2. Heat can be generated at a uniform rate through solid conduction, increasing the heat transfer rate and reducing the loss. Fuel cells can provide self-sufficient fuel without consuming a large amount of energy. With every barrel of shale oil produced, the power generation is 174 kWh. The operating cost of this system is \$30 per barrel, the natural gas and electricity produced will decrease to \$14 per barrel after sales. It has low exhaust emissions because of the lack of combustion and use electrochemical reactions to generate electricity. However, there are some drawbacks, such as high initial cost investment. Fuel cells require long-term operation in high-temperature environments, which has a serious lifespan impact. Power generation has volatility, it is difficult to fully absorb and digest the power grid.

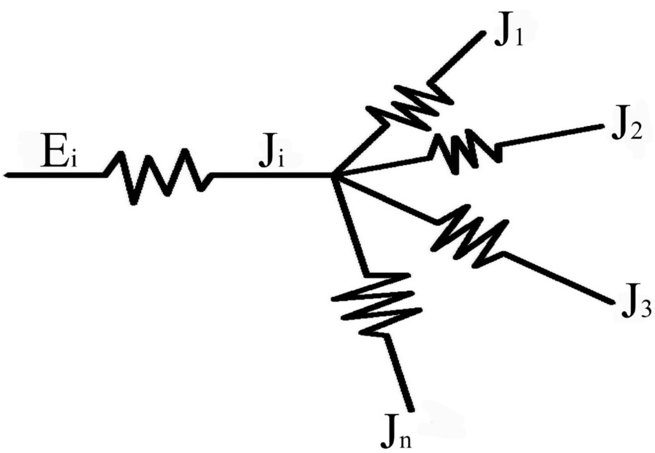

Fig. 2. GFC technology of IEP.

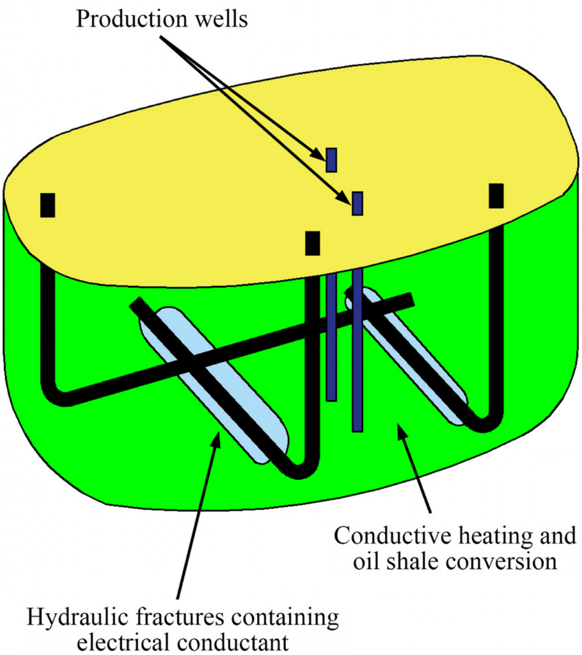

Fig. 3. ICP technology of Shell.

Shell has been studying the ICP technology since 1980. By 2021, it has applied for over 230 patents and conducted numerous pilot tests. The company uses electric heaters to heat oil shale reservoirs, and has created an original freezing wall technology [10–12], as shown in Figure 3. With the advancement of electric heating control, it has evolved from being initially applicable to diameters with well spacing less than 30 m to being successfully used to horizontal wells. This technology can reduce the damage to the surrounding environment and use the frozen wall technique to protect the groundwater. Its weaknesses are high quality requirements for electric heaters, high maintenance costs, small coverage area and specific requirements for the reservoir oil content and thickness.

Shell's ICP technology has successfully operated and extracted oil. However, the drawbacks of its technical principles are difficult to solve. Zhao et al. [40] used the mathematical model of heat conduction to conduct numerical calculations on the ICP development process with a well spacing of 25 m. The results show that it would take 23 years of continuous heating to make the oil shale reservoirs at 2 m around the heat well reach 400 °C. This study indicates that conduction heating is slow and has a significant energy loss, making it unsuitable for large-scale mining.

2.2. Convective heating technology

The process of heat transfer is caused by displacement between parts with different temperatures in the fluid during contact, which occurs in gas and liquid [41]. When the fluid is heated, the density decreases and becomes lighter and rises. The cooler fluid drops and forms a convection cycle. Heat is transferred to the entire system through the fluid convective motion [42].

At any time t_0, we can select a point (x_0,y_0,z_0) in substance D, then take the infinitesimal element dx, dy, dz on each axis. Finally, we can take the infinitesimal element dt in time. We found a tiny cube with two ends of the diagonal (x_0,y_0,z_0), (x_0+dx,y_0+dy,z_0+dz). For this tiny cube, the following equation can be established:

energy accumulation rate = energy rate into the cube – energy rate out of the cube

The energy accumulation rate is expressed as follows:

$$\rho c_p\left(\frac{\partial u\left(x_0,y_0,z_0,t_0\right)}{\partial t}\right)dxdydz\,, \tag{8}$$

where ρ is the density and c_p is the heat capacity.

According to the diffusion law, Equation (8) is written as:

$$dm=-\gamma\left(x,y,z\right)\frac{\partial u}{\partial n}dSdt\,, \tag{9}$$

where $\gamma(x,y,z)$ is the diffusion coefficient, and dm is the mass of the diffusion substance, which passes through an infinitesimal area dS along the normal direction n in the infinitesimal period dt.

(x_0,y_0,z_0,t_0) is arbitrary, the diffusion law may be expanded as follows:

$$\rho c_p\frac{\partial u}{\partial t}=\frac{\partial}{\partial x}\left(\gamma\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(\gamma\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(\gamma\frac{\partial c}{\partial z}\right). \tag{10}$$

Equation (5) is the diffusion equation. If γ is a constant, then the diffusion equation acquires the same form as the heat conduction equation. With the vigorous development of computer technology, people are increasingly paying attention to the accuracy of calculation results. Diffusion coefficient γ has also evolved from assuming constants to molecular or computational simulations. The differences between the heat conduction equation and the diffusion equation in current numerical simulations cannot be equated.

The convective heating technology uses hydraulic fracturing to form many fracture networks in the oil shale reservoirs. With the flowing characteristics, the fluid is used as the medium to transfer heat to the reservoir. The kerogen is pyrolyzed into oil and gas, and then the fluid is used as the driving energy to displace the generated oil and gas [43, 44]. However, the technology still faces problems with heat consumption, thermal fluid storage, and reservoir porosity and permeability after fracturing. According to fluid type, there can be distinguished the following modes of technology: boiling oil, high-temperature air, hydrocarbon gas and water vapor.

The predecessor of the American Shale Oil Company is the EGL Oil Shale, who was a developer of in-situ shale oil extraction technology and was based in Rifle, Colorado. The company has proposed a new in-situ mining technology, namely, the initial design of the conduction, convection and reflux (CCR) process. The technology utilizes the oil boiling as the primary warming method and comprehensively uses convection and reflux methods to transfer heat [17, 18], as shown in Figure 4. Its benefits are the following. The heating efficiency and utilization rate of the reservoir longitudinal convection are significantly improved. The permeability of the reservoir through mechanical fracturing to transfer heat more effectively is increased. Using oil as the heat transfer medium saves water resources. CCR has the following drawbacks. The electric heating technology is complex and requires high-quality electric heaters. The heating efficiency and utilization rate of the reservoir lateral convection are insufficient.

Petro Probe is engaged in developing technologies and related projects for producing oil and natural gas from American oil shale resources. The company has proposed a new in-situ mining technology – superheated air technology. It uses high-temperature air with low oxygen content to heat the oil shale reservoirs, and carries the generated hydrocarbons to the ground in the form of high-temperature gas [13, 14]. The technology has the following advantages. High-temperature compressed air flowing into the reservoir can fracture oil shale, increase the reservoir porosity and permeability, and the rate of hydrocarbons recovery. Part of the hydrocarbon gas can be used as fuel to enter the burner, providing energy self-sufficiency and saving costs. The generated CO_2 can be equivalent to the heat medium – air, which is

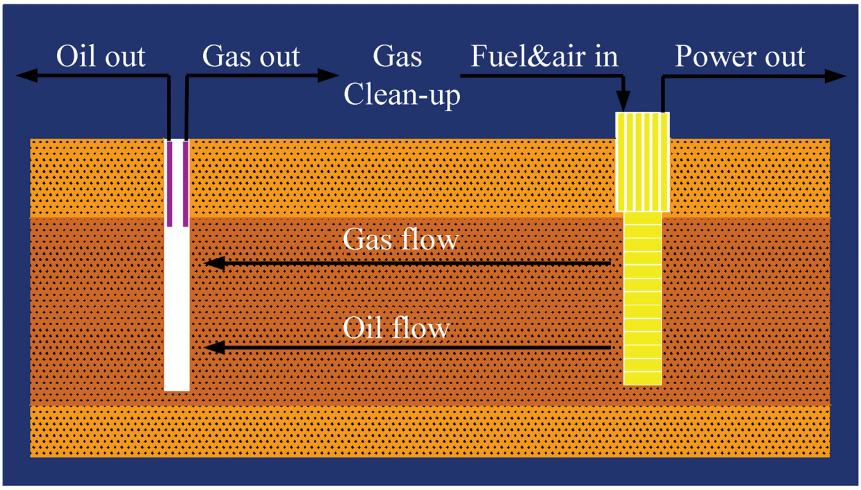

Fig. 4. CCR technology of the U.S. Shale Oil Company.

fully heated and then injected into the reservoir, reducing the environmental pressure. The reservoir retains 94–99% of its original structural integrity. It can develop a reservoir up to 900 m. However, the technology also entails some shortcomings. The groundwater is damaged easily, which can cause water pollution. The control equipment is complex and difficult to operate. The electric heating technology is complex and requires high-quality electric heaters. Both the ground burner and the underground electric heater require long-term maintenance, resulting in higher costs.

Taiyuan University of Technology was granted a patent for high-temperature hydrocarbon gas convection heating oil shale oil and gas exploitation – MTI technology, which was proposed by the University's Mining Technology Institute (MTI) and developed on the basis of superheated water steam convection heating [45]. The superheated water steam convection heating technology arranges multiple wells on the ground, uses fracturing to connect well clusters, and then selects alternately the heat injection and production wells. The steam of 400–700 °C is added into the oil shale ore bed along the heat injection wells, which causes the kerogen to be pyrolyzed into oil and gas. Then kerogen is carried by low-temperature steam or water along the production wells to the ground for separation, and finally oil and gas products are formed [46–48]. The latest research progress has found that high-temperature hydrocarbon gases have higher heat capacity coefficients and greater commercial potential. Industrial experiments on large specimens have been completed in the laboratory, and in-situ mining pilot experiments are conducted in Fukang, Xinjiang currently. This technology exploits the oil shale reservoir by using a high-temperature hydrocarbon gas convection heating method [20], see Figure 5. The method's advantage is that it does not require water as a heat transfer medium, which saves water resources. The high

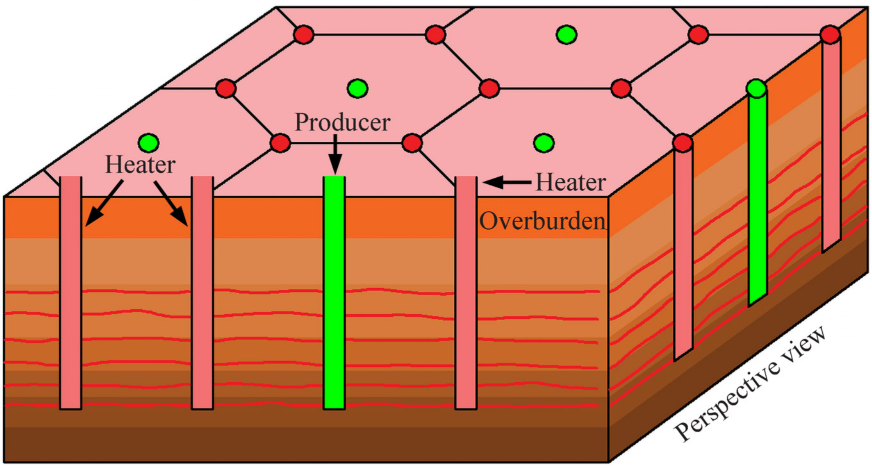

Fig. 5. MTI technology of Taiyuan University of Technology.

heat capacity coefficient of high-temperature hydrocarbon gases increases the heat transfer rate and reduces the heat loss. Using the fracturing technology to connect well clusters increases the reservoir porosity and permeability, and oil recovery efficiency. The rotation of heat injection and production wells ensures that the temperature of oil shale deposits rises evenly and enhances the heat transfer rate. The technology has the following shortcomings. Without isolation measures the underground water gets easily polluted. The technology is unable to ensure good connectivity between wells. It is necessary to have a large natural gas field nearby to supply hydrocarbon gas for heat transfer.

In 2006, Chevron and Los Alamos National Laboratory jointly developed CRUSH technology. This technology uses the fragmentation technique to break rocks and generate numerous fractures to provide a larger contact area. It uses high-temperature media such as steam to heat oil shale and crack kerogen [49, 50]. Chevron has planned to transfer the RD&D lease right of Piceance Basin, Colorado currently. Compared with other convection heating technologies, Chevron's technology has several benefits. The crushing technology increases the porosity and permeability of the reservoir and rises the recycling rate. High-temperature media such as water vapor have good dissipation properties, which enables an even transfer of heat to the reservoir, thereby increasing the heat transfer rate and decreasing the heat loss. The monitoring well monitors real-time downhole data and is able to adjust the injection rate, temperature and other conditions of high-temperature media at any time. The disadvantage is that a large amount of water resources is required to ensure the operation of the system. In addition, the crushing technology may cause significant environmental damage. Failure to protect groundwater may easily lead to water pollution.

Yang et al. [51] and Liu et al. [52] conducted the oil shale distillation experiment by using high-temperature and high-pressure steam. The results show that such steam can effectively retort oil shale and remove shale oil. Oil shale generates large cracks to improve its permeability. The permeability coefficient of oil shale after retorting is a function between volume stress and pore pressure, while this relationship follows the exponential law.

2.3. Radiation heating technology

Radiation is the propagation of heat as electromagnetic waves without a medium [53]. With temperature substances will radiate electromagnetic waves. The total energy radiated grows with increasing temperature. When approaching a stove, one may feel a burning sensation although far from it. The temperature transmitted by the sun to the earth is thermal radiation [54].

As shown in Figure 6, it is assumed that the surfaces involved in radiation heat transfer are closed and the opening surfaces are imagined to be imaginary blackbody surfaces. The faces of objects for radiation heat transfer are transparent media (such as monatomic or diatomic gas with symmetric

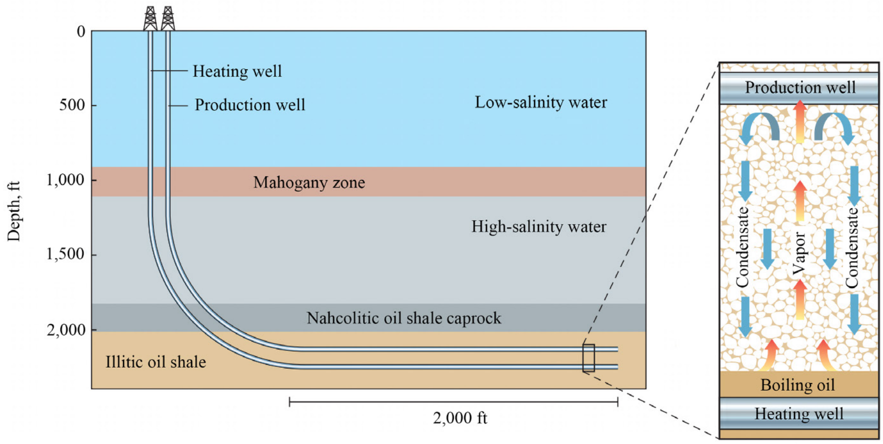

Fig. 6. Radiant heat transfer on the surfaces.

molecular structure, air) or a vacuum. The surfaces of objects participating in radiation heat transfer are diffuse (diffuse emission, diffuse reflection) graybody or blackbody. The temperature, radiation characteristics and input radiation distribution are uniform.

For the analysis of the closed cavity composed of multiple surfaces, the energy balance method can be used. The total radiant heat flow from all surfaces including *i* to *i* surface is expressed by Equation (11):

$$F_i G_i = \sum_{j=1}^{n} F_j J_j X_{j,i} \,. \tag{11}$$

Due to the completeness of the angle coefficient, we get:

$$J_i = J_i \times 1 = J_i \times \sum_{j=1}^{n} X_{i,j} \,. \tag{12}$$

The general expression of the effective radiation of node *i* can be expressed as follows:

$$\frac{E_{bi}}{\frac{1-\varepsilon_i}{\varepsilon_i F_i}} = \sum_{j=1}^{n} \frac{J_i - J_j}{\left(F_i X_{i,j}\right)^{-1}} \,. \tag{13}$$

Figure 7 shows the relationship between the total amount of radiation and its components.

The unknown temperature and the net radiant heat flux of the known surface are given by Equation (14):

$$Q_i = \sum_{j=1}^{n} \frac{J_i - J_j}{\left(F_i X_{i,j}\right)^{-1}} \,. \tag{14}$$

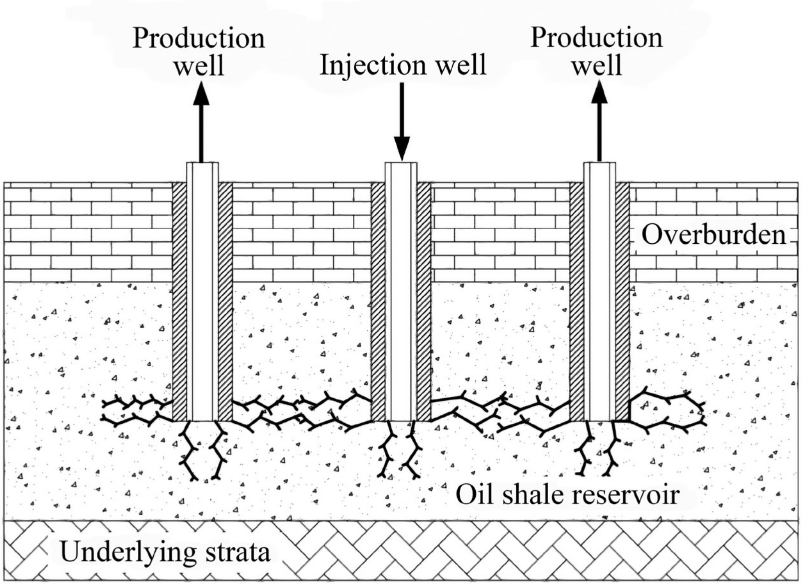

Fig. 7. Relationship between the total amount of radiation and its components.

The radiation heating technology uses microwave. Its electromagnetic energy transmission acts on the molecules, and on heating the rock to decompose kerogen into oil and gas. For displacement special fluids are injected and conventional methods are used to extract kerogen to the surface without heat conduction [55]. The high heating power of the microwave and the high radio frequency can accelerate the rise of the reservoir temperature. High equipment costs and large initial investment have not been applied on site. There are two theoretically most complete radiation heating technologies, namely, Lawrence Livermore National Laboratory's (LLNL) radio frequency (RF) technology and Schlumberger's radio frequency-critical fluids (RF/CF) in-situ mining technology.

In the late 1970s, the Illinois Institute of Technology proposed to use the RF technology to heat oil shale. This process was developed by LLNL. It uses vertical combined electrodes to slowly warm large-particle and deep oil shale through radio frequency [21], as shown in Figure 8.

Raytheon and its technical partner CF Technologies, currently owned by Schlumberger, are engaged in co-developing further the RF/CF in-situ mining technology. The companies aim at working out an in-situ mining technology that could reduce environmental impacts. The technology consists in heating the oil shale reservoirs with radio signals sent by a radio frequency transmitter and extracting generated oil and gas by supercritical CO_2 [22], see Figure 9.

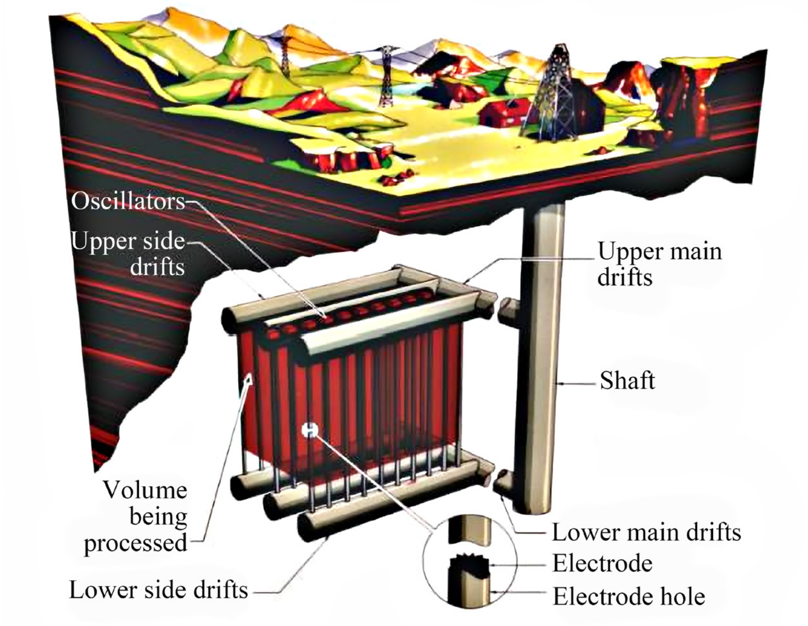

Fig. 8. LLNL RF technology.

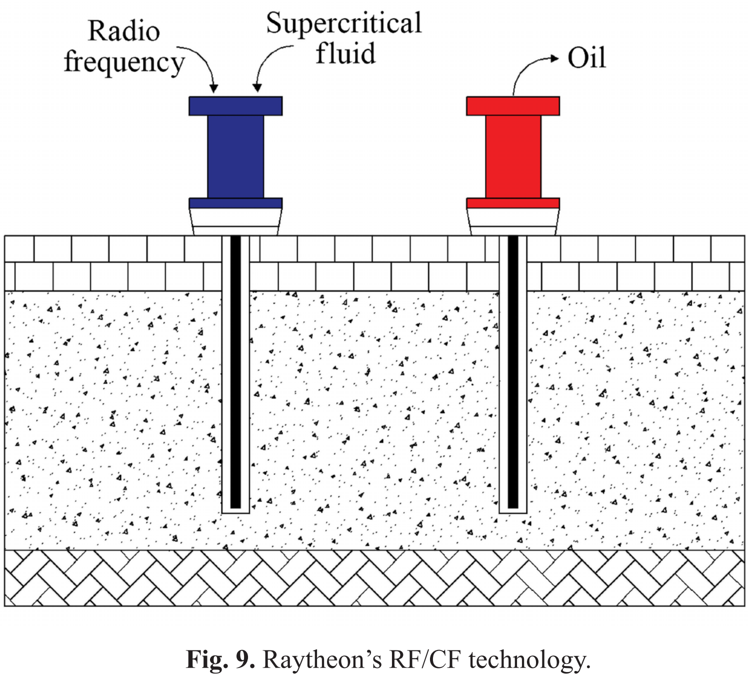

Fig. 9. Raytheon's RF/CF technology.

The radiation heating technology reveals the following strengths: strong penetrability and high exploitability of oil shale with thin reservoirs and low oil content. It can increase the heating rate of oil shale and accelerate the pyrolysis rate of kerogen. The technology is easy to control, turn off and stop immediately. The high heat transfer rate shortens the heating cycle. The shale oil produced by radiation heating has low sulfur content, which causes slight corrosion to production equipment. At the same time, more oil and gas are produced per unit of energy. The shortcomings are as follows. The radio frequency technology is complex and difficult to install, the maintenance costs of the high-precision equipment are high. The reservoir porosity and permeability have not been increased, oil and gas are hard to flow and recycling is low.

Noble et al. [56] and Wang and Noble [57] found that when the power of microwave radiation is 450 W, the shale oil yield is similar to that obtained by using conventional heating. When the microwave radiation reaches 600 W, the oil yield will start to decrease. The research report indicates that during the pyrolysis of kerogen, the rapid rise of temperature will lead to the generation of gas and the pyrolysis reaction of shale oil. Compared with conventional heating, the shale oil produced by microwave radiation contains less asphaltene and polar compounds.

2.4. Combustion heating technology

Combustion is a chemical reaction that emits light and generates heat. Combustion heating technology utilizes the heat energy released during the combustion process to warm. The combustion rate can be expressed as the chemical reaction rate. The chemical reaction rate obeys the mass action law at the same temperature, which is defined by the amount of fuel burned or oxygen consumed per unit of time and volume.

The combustion reaction can be expressed as follows:

$$\begin{array}{ccccc} aA & + & bB & = & gG + hH \\ (\text{Fuel}) & & (\text{Oxidant}) & & (\text{Combustion products}) \end{array}. \tag{15}$$

The chemical reaction rate can be expressed by the forward reaction rate or the reverse reaction rate as:

$$W_A = -\frac{dC_A}{dt}, \tag{16}$$

$$W_B = -\frac{dC_B}{dt}, \tag{17}$$

$$W_G = -\frac{dC_G}{dt}, \tag{18}$$

$$W_H = -\frac{dC_H}{dt}. \tag{19}$$

During the combustion, there takes place a continuous supply of fuel and oxides (air) at a certain ratio. When the mixture is uniform, it can be considered that the combustion reaction is carried out at a constant concentration of the reactant. The relationship between chemical reaction rate, fuel properties and temperature is expressed by Equation (20) which follows the Arrhenius law:

$$k = k_0 e\left(-\frac{E}{RT}\right), \tag{20}$$

where k_0 is equivalent to the coefficient, which is the collision frequency and the effective number of collisions between the molecules of reactive substances in unit concentration; E is the reaction activation energy; R is the general gas constant; T is the reaction temperature; k is the reaction rate constant (constant concentration).

The Arrhenius law reflects the relationship between the "activity" of the fuel itself and the influence of temperature on the chemical reaction rate. The activation energy is based on the theory of molecular motion. As most fuel reactions are bimolecular reactions, the primary condition for these reactions is that two molecules must contact and collide with each other. There are many opportunities for molecules to collide, but not every collision of each molecule can have an effect. If collision works, the combustion reaction will be completed at a low temperature. However, if combustion takes place at a limited rate, collisions of activated molecules are effective [58]. The energy of collision is high. This energy is high enough to destroy the original chemical bonds and form new ones. However, high-energy molecules are rare. In order to be effective, such molecules must be transformed into activated molecules, and the minimum energy required for this transformation is called activation energy, denoted by E. The energy of activated molecules is higher than the average, its effect consists in increasing the number of said molecules.

The combustion heating technology is the same as that of in-situ combustion heating. First, large-scale fracturing or blasting is carried out on the oil shale reservoir to form a large number of fracture spaces. Then, a certain amount of air is injected into the reservoir to burn and release the heat transferring to the reservoir. Finally, kerogen undergoes pyrolysis into oil and gas, which are transported and extracted from the ground through cracks [59, 60]. However, this technology generates a huge amount of exhaust gas, pollutes the air and groundwater, and causes great damage to the structural integrity of the original reservoir. In view of the formation damage, the technologies are divided into true in-situ (TIS technology) and modified in-situ (MIS technology).

TIS technology is an underground in-situ pyrolysis technology of oil shale proposed by the Laramie Energy Technology Center (LETC) in the 1960s. This technology first adds hot gas and air into the reservoirs, and then uses the heat generated by combustion to warm oil shale [25, 26].

MIS technology is a new type of underground in-situ combustion pyrolysis of oil shale proposed by LLNL in the 1970s. It aims to ignite the hot and co-

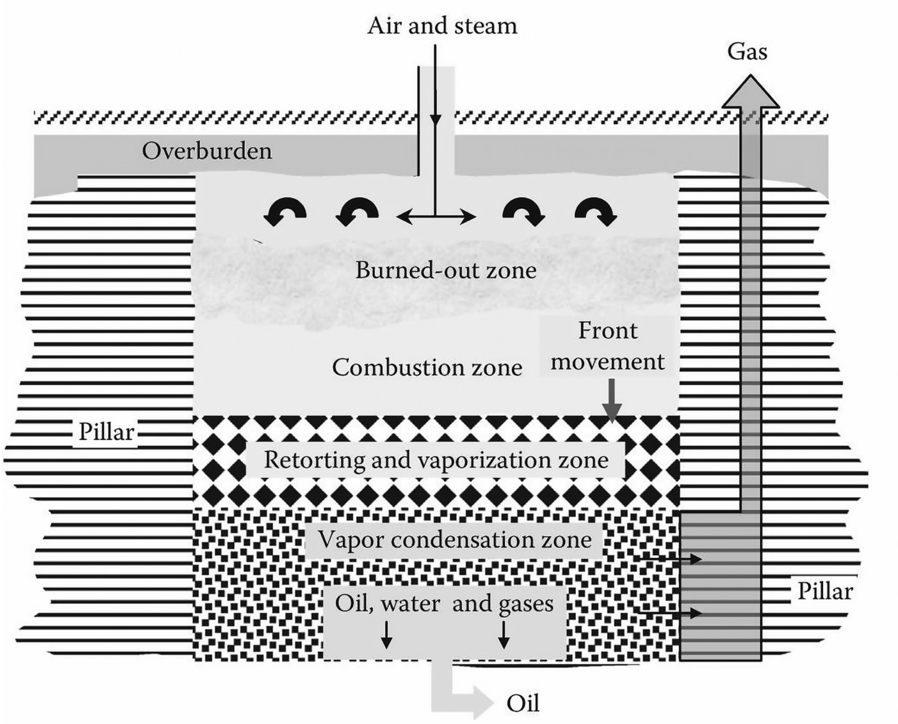

Fig. 10. MIS technology of LLNL.

burnt gas injected into the reservoir and generate a combustion reaction to heat oil shale [25, 26], as shown in Figure 10.

Jilin University and Israeli scientists jointly developed a local chemical reaction method of oil shale in-situ conversion technology (TSA method). It is a chemical heating enhancement craft, rather than a simple physical heating or a complete combustion process, which can achieve in-situ pyrolysis and oil recovery of oil shale without external continuous warming [61]. The purpose is to use the air oxidation reaction to trigger a strong chemical heating oil shale reservoir [27], see Figure 11.

The technology can be distinguished by the following characteristics. Massive water resources are saved without participation of water. The high heat transfer rate reduces losses. The technology is easy to implement repeatedly and the process is controllable. The quality of shale oil produced is similar to that obtained by underground retorting. The technology's drawbacks are that it damages the structural integrity of the original reservoir and is prone to cause groundwater pollution. Also, improper control may lead to the extensive burning of shale oil.

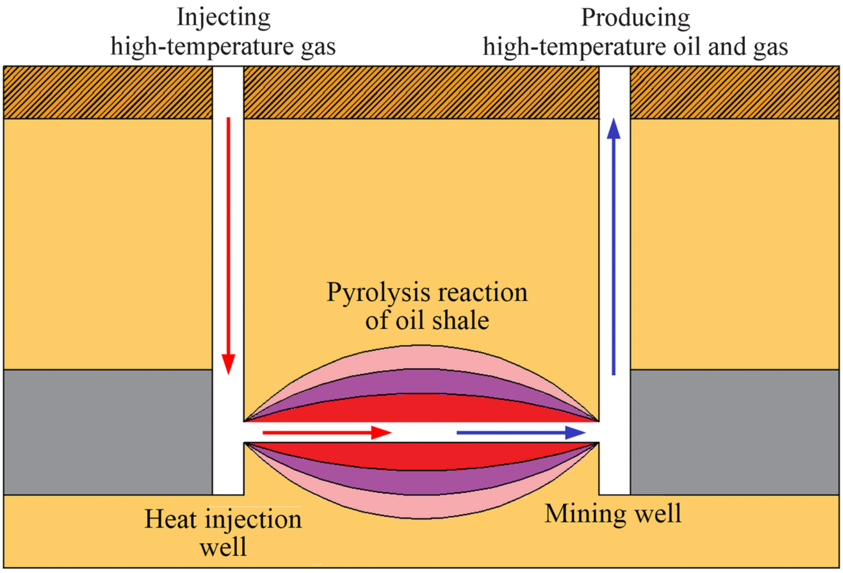

Fig. 11. TSA method of Jilin University.

Han et al. [62] and Han et al. [63] studied the pore structure evolution of shale ash after combustion and the oil shale combustion mechanism. It was ascertained that the high-temperature combustion process causes particle melting.

3. Summary

Oil shale is an important strategic resource for human society development and support for the future social energy structure. The rise of in-situ mining in recent years is expected to become an effective way for oil shale large-scale commercial exploitation. This article introduces the heat transfer principle of in-situ mining technology and its progress worldwide. The following conclusions can be made:

1. The new in-situ oil shale mining technology developed institutes technical methods and control measures for environmental protection, avoids or minimizes the environmental impact and monitors and adjusts air, soil and groundwater information anytime.
2. The in-situ mining technology should be simple and intelligent with low cost and high efficiency as important goals and directions in the future.
3. The integration and application of various technologies is one of the ways for the in-situ mining technology development. Numerical simulation

technology is widely used in process modeling and simulation research, and mega data intelligent application in underground real-time well condition monitoring. They can accelerate the advancement and application of the in-situ mining technology.

4. With the construction of a modern energy system, the world continuously promotes carbon peaking and carbon neutrality. Carbon Capture, Utilization and Storage technology can be applied to the oil shale in-situ mining process to achieve green and low-carbon oil industry. Applying CO_2 enriched by capture technology in convective heating has received considerable attention in recent years, which is beneficial to supercritical CO_2 heating technology.

The existing theoretical framework of oil shale in-situ mining technology is not ripe. The research on metallogenic theory and resource evaluation methods is limited. The numerical simulation data of oil shale reservoir fracturing and temperature field is not sufficient. The pollution of fracking on groundwater and the massive consumption of water resources mean that large-scale commercial exploitation of oil shale cannot be carried out. It is a huge challenge for the oil shale industry. The oil shale in-situ mining should be comprehensively optimized and advanced technologies from other industries should be introduced. Today the convective heating technology has the most promising development potential. The following is suggested to optimize this technology. First, the high-energy gas fracturing has to be introduced, which can reduce the fracturing pressure of the formation, improve the effective penetration rate of perforation, and exerts no pollution on the oil shale layers. Second, CO_2 or supercritical CO_2 is to be used as the heat transfer medium, which improves the CO_2 utilization and promotes the development of carbon capture. Third, after mining, carbon sequestration treatment can be carried out on the formation. CO_2 can replace and adsorb CH_4 on the shale to achieve CO_2 permanent burial and prevent CH_4 from polluting the groundwater. Fourth, it is necessary to introduce mega data and intelligent integrated system to improve work efficiency and accuracy of data analysis. Also, it is essential to reduce the waste of human resources, effectively control the temperature of the heating medium and the injection speed to decrease costs.

The world's oil shale resources are rich in reserves and have huge exploitable potential. Underground in-situ mining technology is the oil shale development direction in the future. Due to the complexity and difficulty of achieving commercial application, it is necessary to carry out extensive scientific research in related theories, technologies and equipment, such as heating efficiency, horizontal well guided drilling and composite reservoir transformation technology. The industrial, green, information-based and intelligent integrated development is the oil shale in-situ mining mode in the future. The oil shale commercialization is aimed at low cost, high production and low pollution. Issues to be researched and solved include resources, technology, economy, and society.

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