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Oil shale electric heater and its optimization: a review

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Abstract. *Oil shale is a type of unconventional energy with abundant reserves. In the in situ mining technology of oil shale, electric heating technology has become a research hotspot due to its multiple advantages, and electric heater is the core of this technology. Despite growing interest in electric heating for in situ oil shale extraction, there remains a lack of comprehensive reviews that focus specifically on the electric heater – its types, performance characteristics, and design optimization strategies. In this paper, the oil shale electric heater is taken as the research object. First, the four mainstream oil shale electric heating technologies – Shell's in situ conversion process, ExxonMobil's Electrofrac™, geothermal fuel cell, and high-voltage power frequency electric heating technology – are analyzed, and their principles, characteristics, and limitations are elaborated in detail. Subsequently, the research status of electric heaters is discussed in depth, covering various types of heaters and their performance, and existing problems are identified. The key role of numerical simulation technology in the optimal design of electric heaters is emphasized. In the future, structural innovation and numerical simulation technology should be leveraged to further optimize the performance of oil shale electric heaters, continuously improving their heat efficiency, thereby promoting their extensive application in industrial fields.*

Keywords: *oil shale electric heater, in situ mining, electric heating technology, numerical simulation.*

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1. Introduction

Energy is the driving force behind social production and the advancement of people's lives, making it highly significant for social and economic development. With the continuous depletion of traditional petroleum energy reserves, the development and utilization of unconventional energy sources have gradually gained attention [1–3]. Among them, oil shale is a type of unconventional energy with abundant reserves. Its proven shale oil reserves worldwide are about 457 billion tons, which is equivalent to 5.4 times the recoverable reserves of natural crude oil. Therefore, it is also considered as an important alternative energy source to oil [4, 5]. Through the exploitation of oil shale, shale oil is obtained by condensation and recovery from the retorting process [6]. Diesel and gasoline fractions can be extracted through deep hydrogenation, which can replace part of conventional oil and natural gas and can be directly used in ships, automobiles, and other industrial fields, greatly alleviating the pressure on energy supply [7].

At present, conventional oil shale mining methods, both domestic and international, are divided into above-ground retorting and in situ mining. In above-ground, oil shale is first mined and then heated in a retorting furnace, producing shale oil, pyrolysis oil and gas, and solid residual coke through pyrolysis. This method presents problems such as high energy consumption, environmental pollution, and low resource utilization [8–10]. In contrast, in situ mining involves directly heating the underground oil shale layer to extract oil and gas. It offers the advantages of high product quality, improved oil recovery, a small surface footprint, and reduced environmental protection, making it suitable for deep and thick oil shale reservoirs [11, 12].

The core of in situ mining lies in heating the oil shale reservoir. Depending on the heating technology used, it can be divided into electric heating, fluid heating, radiation heating, and combustion heating [13, 14]. Among these, electric heating stands out due to its simple operation, convenient construction, small footprint, adjustable temperature, and wide application range. It has become the preferred solution for industrial applications [15].

Current mainstream electric heating technologies include Shell's in situ conversion process (ICP) [16], ExxonMobil's Electrofrac™ [17], Independent Energy Partners' (IEP) geothermal fuel cell (GFC) technology [18], and high-voltage power frequency electric heating (HVF) technology [19]. These technologies all rely on electric conduction heating to pyrolyze oil shale, but they differ significantly in heating efficiency, operational cycles, and engineering adaptability. Therefore, it is necessary to systematically review their principles and limitations to clarify the future direction of electric heating technologies. It is worth noting that, as the core component of electric heating systems, the performance of electric heaters directly affects heating efficiency and system stability [20]. However, existing heaters face challenges such as local overheating, high energy consumption, and maintenance difficulties.

Technical breakthroughs still need to be achieved through material innovation, structural optimization, and numerical simulation.

Although some progress has been made in the research on electric heating technology, there is no systematic review of its core component – the electric heater. This paper focuses on the oil shale electric heater. First, the principles, characteristics, and limitations of four representative electric heating technologies are analyzed. Second, the current research status and directions for optimization of electric heaters are summarized. Finally, the supporting role of numerical simulation in heater design is discussed to provide a theoretical reference for the industrial application of in situ electric heating technology in oil shale extraction.

2. Oil shale electric heating technology

2.1. Principle of electric heating technology for oil shale

The oil shale electric heating method is represented by Shell's ICP technology, ExxonMobil's Electrofrac™ technology, IEP's GFC, and the in situ HVF technology developed by Jilin University and Tomsk University of Technology [21]. The following section analyzes the principles and limitations of these four electric heating technologies.

As shown in Figure 1(a), the in situ mining technology using high-voltage, industrial-frequency electric heating is a conduction heating method [22]. Boreholes are drilled into the oil shale reservoir, and positive and negative electrodes are placed into separate boreholes. A high voltage is applied between the electrodes to change and carbonize the underground pool, thereby reducing its electrical resistance. Then, using industrial-frequency electricity, a current is introduced into the reservoir through the pre-installed electrodes. This current heats the oil shale through the ionophore channel formed in front and the reduced resistance. Finally, hydrocarbons generated by pyrolysis are extracted through a production well.

The advantages of this technology include fast heating speed, short heating cycle, and low pollution. Compared with traditional oil shale heating and pyrolysis technologies, this method achieves in situ heating through drilling, eliminating the need for surface mining and processing, thereby reducing the ecological damage caused by excavation in conventional methods, as well as the pollution from waste gases and wastewater generated by surface pyrolysis. The disadvantage is the short effective distance of the heating process, which is still in the experimental development and perfection stage and requires further research and optimization.

As shown in Fig. 1b, the ICP technology is a conduction heating method [23]. This technology was developed by Shell Netherlands [16]. The principle involves installing heating cables in the target heating zone of the oil shale reservoir, setting the power and temperature of the electric heater,

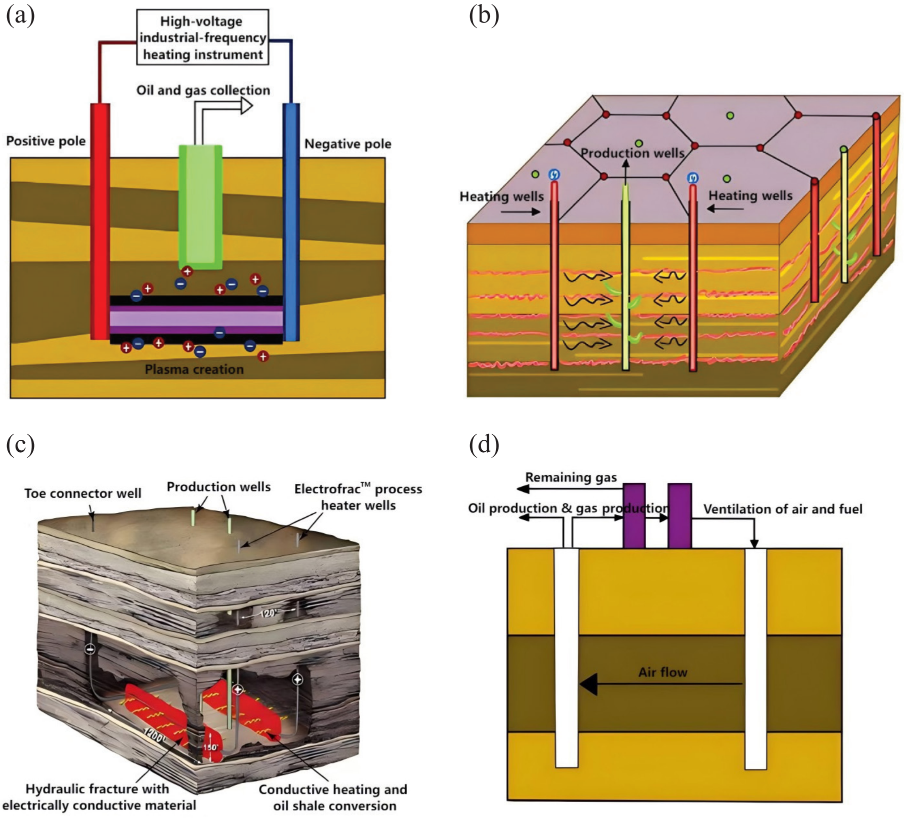

Fig. 1. Conduction heating technology: (a) high-voltage industrial-frequency electric heating technology; (b) ICP technology [28]; (c) Electrofrac™ technology [28]; (d) IEP's GFC technology.

and cracking the oily kerogen in the reservoir through conduction heating to produce light oil shale oil and natural gas. Moreover, the pyrolysis process simultaneously improves the permeability and porosity of the reservoir, creating percolation channels for transporting the produced hydrocarbons [24]. Finally, with the help of production wells, the pyrolyzed light oil and gas are extracted from the subsurface using conventional oil recovery processes [25]. This is one of the most mature techniques currently applied in practice.

Shell's ICP in situ recovery technology has the advantages of high recovery rates, a small footprint, direct heating of deep oil shale, and adequate environmental protection compared to conventional dry distillation technology. However, since this technology relies on heat transfer to heat the reservoir, there are inherent limitations that lead to a long development cycle, with a typical heating time of about two to four years and a low energy utilization rate [26].

The Electrofrac™ technology (Fig. 1c) is an in situ extraction method developed by ExxonMobil in the United States [17, 27]. It involves fracturing the subsurface oil shale reservoir, to create a number of cracks. Then, conductive proppant is injected into the fractures to form electrically conductive heaters within the oil shale reservoir. Using the pre-designed electric heating wells and specified electric heating power, the reservoir is heated through conduction [28]. As the oil shale is heated by heat transfer, the kerogen in the pool is fractured. Eventually, the resulting light oil and natural gas are extracted through production wells.

The advantage of this technology is that by employing fractures with conductive proppant, a heating plane is formed, which provides a more extensive heating range and higher heating efficiency than the linear heating of ICP in situ extraction technology. It also requires a relatively small number of heating wells and has less impact on the surface environment. However, a disadvantage is that although the heating time is shorter than that of ICP, it still involves long heating cycles and slow heat transfer. Additionally, a freeze wall must be designed to protect the heating layer.

As shown in Figure 1d, GFC technology is an in situ extraction method developed by the Institute for Clean and Secure Energy in the U.S. In this method, a fuel cell is used as the heating medium. A fuel cell device is installed in an underground oil shale reservoir, and fuel (natural gas) and air are introduced into the reservoir to generate heat through a chemical reaction. The oil shale is then pyrolyzed via conduction heating [18]. At the same time, a portion of the extracted natural gas is injected into the downhole heating unit, allowing the oil shale reservoir to continue pyrolyzing, thus enabling energy recycling.

The advantage of this method is that it is highly environmentally friendly and allows for energy recycling, making the cost relatively low. However, due to certain limitations, the heating rate is slow, and the heating period is extended.

3. Oil shale electric heater

The electric heater, as the core component of electric heating technology, has performance directly related to the efficiency and effectiveness of in situ mining [29].

3.1. Research status of oil shale electric heaters

Downhole electric heaters are core equipment for in situ mining of oil shale. Their working principle involves generating heat through resistive elements inside the electric heater, converting electrical energy into thermal energy, which then heats the surrounding reservoir via thermal conduction, thereby achieving efficient extraction of oil shale [30, 31]. Previous studies have

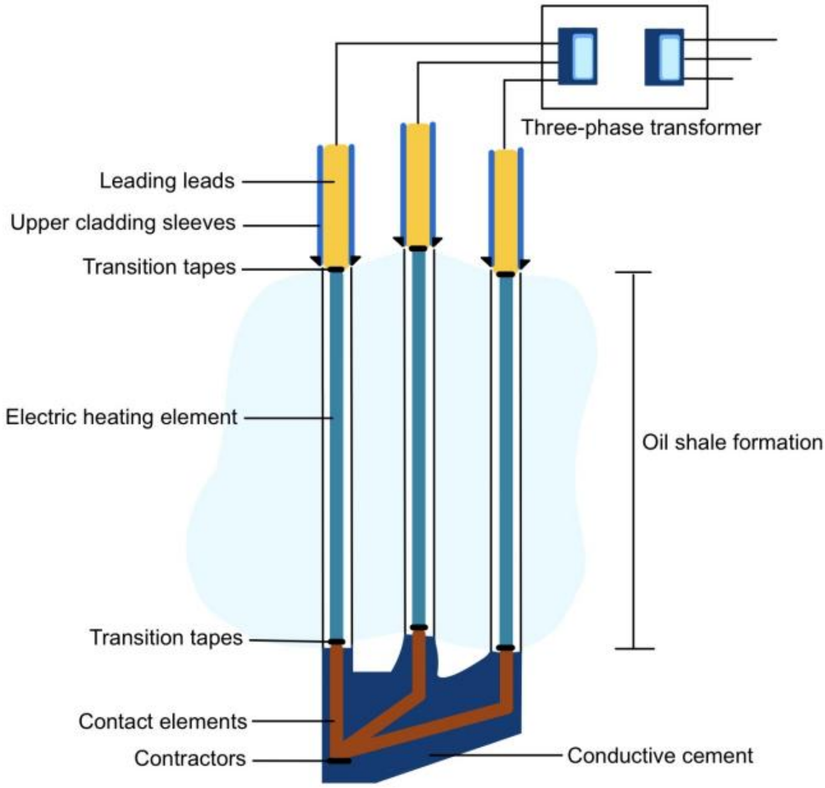

Fig. 2. Y-type electric heater [33].

primarily focused on the impact of different structural configurations of heaters on performance.

The Y-type electric heater is shown in Figure 2. Shell applied this electric heater in the experimental project of in situ electric heating extraction technology for oil shale (E-ICP) in 2006, laying the foundation for the subsequent development of oil shale electric heaters [32].

Wang et al. [33] designed U-type and LU-type electric heaters based on the Y-type electric heater, as shown in Figure 3a and b. U-type heaters are suitable for extracting thin-layer oil shale, but this type of heater requires drilling multiple horizontal and directional wells during implementation, resulting in high construction costs and significant complexity. The LU-type electric heater uses a linear arrangement of three heaters, electrically connected to the surface and horizontal wells through wires and contact elements, forming a tripartite structure. This design provides more flexible and diverse electrical connection options, significantly reducing construction difficulty. However, its linear arrangement has inherent drawbacks when heating oil shale layers, resulting in suboptimal thermal efficiency.

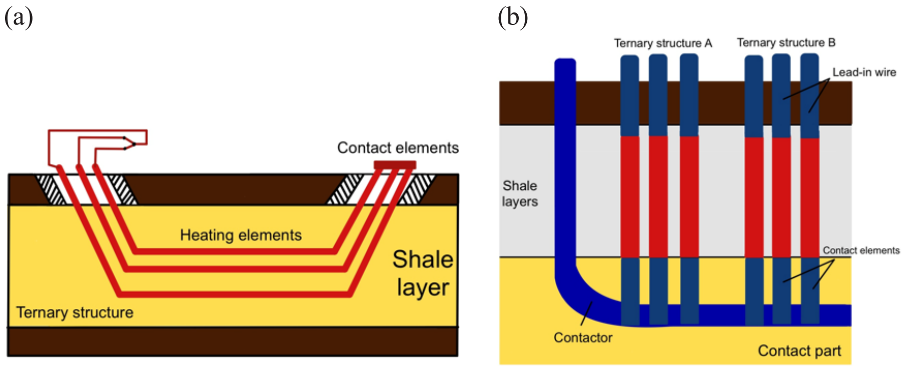

Fig. 3. (a) U-type electric heater; (b) LU-type electric heater [33].

Figure 4a and b illustrate two types of downhole electric heaters developed by Ojeda and Parman [34]: the mineral insulated (MI) electric heater and the constant wattage (CW) electric heater. The MI electric heater exhibits high-temperature resistance and strong corrosion resistance, making it an ideal choice for deep well environments with high temperatures and strong corrosion, but its manufacturing cost is relatively high. The CW electric heater is specifically designed for geothermal decomposition reactions in medium-deep (burial depth >350 m) low-permeability tight rock formations, serving as an optimal solution for medium-deep low-permeability oil and gas reservoirs under geologically stable, moderately corrosive, and explosion-proof conditions. However, it features a complex structure, high installation difficulty, requires periodic replacement of seals, and carries a risk of scaling.

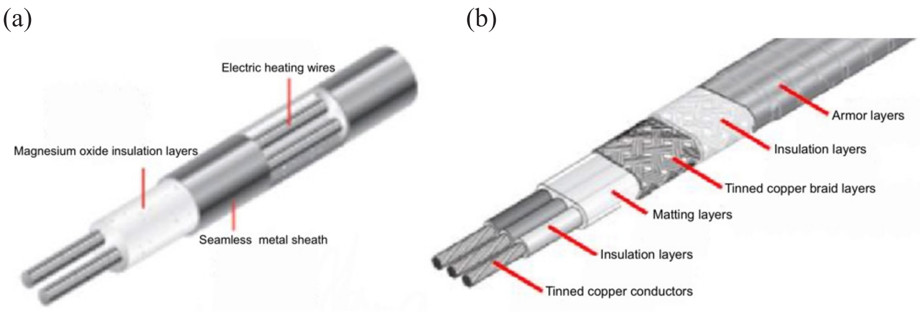

Fig. 4. (a) MI electric heater; (b) CW electric heater [34].

Xie [35] designed an electromagnetic induction heater for downhole applications. Its core principle involves first converting electrical energy into electromagnetic energy using an intermediate-frequency power supply, then transforming the electromagnetic energy into thermal energy via heating elements, ultimately generating high-temperature steam.

The conventional segmental baffle electric heater is widely used and has a simple structure, but there is a flow dead zone on the leeward side of the segmental baffle, resulting in poor overall performance [36, 37]. To overcome this defect, Lutcha and Nemcansky [38] successfully developed a helical baffle structure. This design effectively eliminates the flow dead zone, causing the fluid in the shell side to exhibit a nearly plug flow pattern, significantly improving heat transfer efficiency and achieving flow uniformity, thereby greatly enhancing overall performance.

The helical baffle electric heater uses electric heating rods as the heat source, heating the shell-side air to a high-temperature state through an enhanced heat transfer structure and injecting it into the formation. The helical baffle can strengthen the shell-side heat transfer capability of the enhanced heat exchange structure by increasing the shell-side turbulence effect and prolong the heater's lifespan [39]. Guo et al. [40] were the first to successfully apply a heat transfer structure with continuous helical baffles to the in situ pyrolysis of oil shale. Through experiments and numerical simulations, they found that compared to traditional segmental baffle structures, the continuous helical baffle structure achieves more uniform shell-side flow and higher heating efficiency. Therefore, in terms of long-term operational stability, the continuous helical baffle heater is more suitable for downhole heating.

By introducing a continuous helical baffle structure, the heat transfer efficiency and heating uniformity of the electric heater are significantly improved. Additionally, a design incorporating a double-shell structure can further enhance heating efficiency and effectively reduce heat loss [41]. Wang et al. [42] developed a double-shell downhole electric heater (DS-DEH) with continuous helical baffles. This heater directs air to flow sequentially through the inner and outer shell channels, not only reducing the heat loss associated with single-shell electric heaters but also recycling the heat to preheat the incoming air. They compared its performance with that of a single-shell heater through experiments. The results show that the double-shell structure reduces total heat loss by 87.16–96.41%, increases heating efficiency by 1.06–1.17 times, and effectively improves overall heating performance.

Liu et al. [43] further conducted numerical simulations to analyze the performance of downhole electric heaters with continuous helical baffles. First, they constructed separate physical models for the downhole heater and oil shale heating process. Then, numerical simulations of these models were performed using Fluent software. The results show that the heater achieves optimal performance at a power of 10 kW and a mass flow rate of 0.01624 kg/s. Among the tested configurations, Model IV exhibited the shortest heating time, the fastest oil production rate, and the lowest cumulative power consumption.

Table 1. Classification, heating method, efficiency, cost, complexity, and field applicability of some oil shale electric heaters

Electric heater	Heating method	Efficiency	Cost	Complexity	Field applicability
Y-type electric heater	Conduction heating	Relatively low thermal conductivity efficiency due to electrical resistance	Moderate equipment cost; relatively high energy consumption expenses	Complex structure requiring multi-well collaborative construction; difficult to repair	Applicable to thick oil shale layers
U-type electric heater	Conduction heating	High thermal efficiency due to large contact area and uniform heat distribution	High construction cost; energy-efficient operation with good long-term economic performance	Compact structure; requires multiple horizontal and directional wells, making implementation complex	Applicable to thin-layer oil shale
LU-type electric heater	Conduction heating	Relatively low heating efficiency due to linear arrangement and uneven heat distribution	High construction cost; low operation and maintenance expenses	Structurally diverse; low implementation difficulty	Moderate adaptability to oil shale formations
MI electric heater	Conduction heating	High thermal efficiency; insulation reduces heat loss	High initial cost; low operation and maintenance expenses	Simple structure; long service life; extremely low structural risk	Suitable for deep wells with high temperatures and highly corrosive environments
CW electric heater	Forced convection heating	Thermal efficiency >90%	Moderate equipment cost	Complex structure; requires regular seal maintenance; moderate scaling risk	Applicable to unconventional resource development in medium-deep formations

Table 1 (continued)

Electric heater	Heating method	Efficiency	Cost	Complexity	Field applicability
Downhole electromagnetic heater	Radiation heating	Thermal efficiency ≥98%	High equipment cost; energy-saving rate up to 48%	Easy installation; requires customized temperature control system	Applicable to vertical wells; not applicable to horizontal wells
Segmental baffle electric heater	Forced convection heating	Lower heat exchange efficiency compared to helical baffle design	Low manufacturing cost due to simple structure	Simple construction; no complex processes involved	Widely used in industrial heat exchange applications
Helical baffle electric heater	Forced convection heating	Higher heat transfer coefficient and improved overall performance vs. segmental design	Higher processing and manufacturing costs	Complex tube bundle assembly; pitch design affects flow field optimization	Suitable for high-viscosity fluids (e.g., crude oil); reduces scaling and vibration
DS-DEH (double-shell downhole electric heater)	Forced convection + radiation heating	Heating efficiency 1.06–1.17 times that of single-shell heaters	5–10% higher cost than that of single-shell heaters; saves 20–30% heat exchange area	Complex double-casing structure; requires coordinated flow field optimization with packers	Suitable for high-temperature heat injection in underground wells; reduces heat loss
Innovative downhole electric tubular resistive heater by Chen et al. [44]	Conduction heating	Thermal efficiency >90%; performance improved by 40%	Moderate initial cost; 5% saving in heating materials; >10-year service life	Simple structure without enhanced components	Outlet temperature up to 900 °C; suitable for complex downhole conditions

Chen et al. [44] proposed an innovative design for a downhole electric tubular resistive heater. This heater features a novel structure in which the heating fluid flows through multiple parallel tubes, and enhances heat transfer performance by optimizing parameters such as the inner diameter, length, and inlet flow rate of the heating tubes. This design provides a more efficient solution for in situ oil shale extraction.

Oil shale electric heaters are evolving toward higher efficiency and lower energy consumption (Table 1). Structural optimizations (such as helical baffle and double-shell designs) and the application of new technologies are key to enhancing heating performance. Numerical simulations play a crucial role in optimizing design and operational parameters. Future research should continue to focus on developing more efficient, stable, and geologically adaptable electric heaters to advance the industrialization of in situ oil shale extraction via electric heating technology.

3.2. Optimizing electric heaters with numerical simulation

In the ongoing development of electric heating extraction technology for oil shale, the electric heater, as the core equipment, must be continually optimized. Although traditional experimental research methods can provide valuable data, they are often costly, time-consuming, and ill-suited for thoroughly exploring the effects of various factors under complex conditions. With advances in computer technology, numerical simulation plays an increasingly important role in optimizing the design of electric heaters [45]. It can quickly and flexibly adjust and analyze various parameters in a virtual environment, providing strong technical support for improving the performance of electric heaters.

Yang et al. [29] used the Partial Differential Equation (PDE) of MATLAB to simulate the temperature distribution of electric heaters and concluded that heat production, density, and heat capacity have a significant impact on temperature distribution, whereas the effect of thermal conductivity can be ignored. Heater temperature rises significantly with increasing heat production and heater radius, while higher heat capacity uniformly lowers overall temperature. In addition, they identified copper and stainless steel as preferred heating materials. The optimal design of the heater was found to be an axisymmetric U-tube equipped with a vacuum heating tube.

Zeng et al. [46] used the PDE toolbox of MATLAB to simulate the temperature distribution of electric heaters. They analyzed the effects of key parameters such as thermal conductivity, heat source density, density, specific heat capacity, and heater size on the thermal effect, aiming to provide a basis for optimizing the design of electric heaters. The research results showed that using materials with lower heat density can improve the heating efficiency of the heater; the effect of thermal conductivity on temperature is relatively small; the higher the specific heat capacity, the lower the overall temperature of the heater; and the temperature of the heater will significantly rise with the increase of heat source density. Through orthogonal experimental analysis, it was found that heat source density, density, and specific heat capacity have a significant effect on the temperature distribution of the heater, while the effect of thermal conductivity is smaller. In addition, the temperature of the heater rises with the increase of the radius.

Bu et al. [47] conducted a numerical heat transfer simulation on large-scale spiral baffle underground heaters, and the results showed that the gas heating process of the heater can be divided into three stages: rapid heating, stable heating, and overheating, determined by the temperature distribution and temperature change on the surface of the heating rod. Due to the large volume of the heater, a larger volume and area can be used for heating the heating rod, thereby enhancing the heating performance of the heater.

Numerical simulation provides a new perspective and an efficient means for the optimization of oil shale electric heaters. Through simulation analysis of different parameters, researchers can gain a deeper understanding of the influence mechanisms of various factors on the performance of electric heaters, thereby providing a scientific basis for designing more efficient, stable, and energy-saving electric heaters.

4. Conclusions

Although mainstream electric heating technologies have introduced new possibilities for in situ oil shale extraction, the industrialization process remains constrained by bottlenecks in the energy efficiency and stability of electric heating equipment. This paper presents an in-depth exploration of the structural types, performance characteristics, and numerical simulation applications of electric heaters, drawing the following conclusions:

1. Optimizing the performance of electric heaters is the key breakthrough for enhancing heating efficiency. Current mainstream electric heating technologies (ICP, Electrofrac™, GFC, and HVF) differ in heating mechanisms but commonly face challenges such as slow heating rates, long heating cycles, and limited geological adaptability. Future breakthroughs need to focus on the electric heater itself: first, by improving heat transfer uniformity and energy utilization through structural innovation; second, by developing high-performance materials and new heating modes to withstand the high-temperature, high-pressure environments of deep reservoirs, thus achieving a synergistic improvement in heating efficiency and equipment lifespan.
2. Numerical simulation is driving electric heater design toward refinement and intelligence. Through multi-parameter coupling analysis (thermal conductivity, heat source density, material property parameters), numerical simulation technology accurately quantifies the influence of various factors on temperature field distribution and heat transfer

efficiency, becoming a crucial tool for optimizing electric heater design. With the integration of multi-physics coupling simulations and machine learning algorithms, numerical simulation will accelerate performance improvements in electric heaters, promoting a leap forward in the development of high-efficiency, intelligent in situ oil shale extraction technologies.

Data availability statement

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

Acknowledgments

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